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THE UNITED KINGDOM FEASIBILITY STUDY ON ENERGY FROM SEA WAVES (WESC(76)48A)

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The United Kingdom Feasibility Study on Energy from Sea Waves

1. Introduction

The British Government has for some time been re-assessing the prospects for widening the country's resources base by harnessing the renewable sources (Solar, wind, tides, ocean waves and geothermal sources). Studies which have been made to date have indicated that the energy in ocean waves is intrinsically the most attractive of these sources for the UK based on present evidence. In its study on Energy Conservation in 1974, the Central Policy Review Staff (CPRS) recommended that the first stage of a full technical and economic appraisal of harnessing wave energy for electricity generation should be put in hand. The recommendation led to the commissioning of a preliminary technical evaluation at the National Engineering Laboratory[1]. The main aim of this and further work is to establish, with reasonable confidence, whether it is technically feasible to recover wave energy on a large scale by conversion to more useful forms such as electricity and, if so, at what overall cost compared with competing energy sources in the future.

2. The Resource

Wave power can be readily seen to be a self renewing energy resource of global magnitude, since the source is ultimately solar radiation, large scale meteorlogical wind systems being the intermediaries with the worlds oceans acting as large scale energy buffers. The arithmetic required to make a rough estimate of the magnitude of wave energy is undemanding. The ~~average~~ significant wave height - in metres - is squared and multiplied by half the period in seconds to give the power in kilowatts crossing a metre of frontage. For example an 8 second wave of $2\frac{1}{2}$ metres significant height contains 25 kW/metre. This is a very common energy level world wide and implies massive quantities, since the energy crossing a single quadrant line of the globe - 10,000 kilometres - yields 10,000,000 x 50,000 = 500 gigawatts. This is comparable to the output of the world's total installed electrical generating capacity. We feel it somewhat surprising that very little attention has been paid to a resource of such size. An appreciation of the scale of power available will perhaps encourage the members of this body to consider its possibilities in the light of their own energy situations.

3. Proposed Programme

The Department of Energy has set up a Wave Energy Steering Committee (WESC) with representatives from Department of Energy, Department of Industry, the Central Electricity Generating Board, the Science Research Council and the Energy Technology Support Unit (ETSU).

This Committee has now set out the first stage of a national programme, aimed at establishing the feasibility of the large-scale extraction of power from sea waves. The main features are described here:-

(A) Wave Energy Converter Devices

It has been decided that a number of specific devices, based on different modes of wave to mechanical energy transfer, should be selected for further investigation. The first priority must therefore be given to establishing the credibility of these devices by means of a programme of model tests carried out at 1/100 scale in test tanks together with supporting theoretical analysis and preliminary practical engineering design. It is hoped that this programme will generate sufficient information to enable the cost of further development to be estimated and to allow a decision to be made to proceed to a further programme based on 1/20th scale model test tank and eventually sea going trials.

Three of the devices being studied are:-

1. Salter's ducks described in ref. 2
2. Contouring rafts described in ref. 3
3. The Air pressure ring buoy described in Ref 4

(B) Generic Work

In order to give rigour to the conclusions reached by the work on device models, a supporting set of programmes is suggested to examine problems which will be common to any device. These should deal with the collection and analysis of wave data; wave loading and the effect on structures; performance in normal and storm conditions; anchoring and mooring problems; power generation and power transmission. It will also be necessary to make an assessment of the value to the national system of a varying and partly unpredictable supply of energy. In addition, preliminary studies will be undertaken of the possible effects upon navigation of large scale installations and of the environmental effects of changes in coastal water behaviour.

Specifically the subjects of interest may be described as follows:-

Wave data

To examine existing wave data and the information requirements of device teams and make recommendations as to the need to gather further information, and as to the work involved in presenting existing data in the most convenient form.

Fluid Loading

To examine existing information and theory on the loading of structures by waves and to recommend particular programmes of work if considered necessary.

Structural response

To examine the behaviour, under fluid loading, of structures which are intended to extract part of the incident wave energy; and to make recommendations as to the safe design of such structures.

Anchoring

To examine the anchoring requirements of wave energy devices and recommend the most suitable form of anchor. To recommend further work if necessary to establish the station keeping properties of wave energy devices.

Generation and Transmission

To consider the various alternatives of transmitting energy from wave energy converters to shore, and make recommendations about the most suitable forms of conversion of mechanical energy into a transmittable resource.

Environmental Aspects

To examine the likely effects of large scale deployment of wave energy converters off shore and make recommendations for more detailed studies if considered necessary.

4. Recommendations

Member Countries are invited to note the potential of wave energy as outlined in this paper and to agree on the following actions:-

(a) To exchange information on the estimated size of the recoverable energy resources at different locations in the world and on the variation of the energy available with time.

(b) To stimulate in participating countries studies of the problems which are common to any development of wave energy convertors, including the following:-

(i) The assembly of wave data in a form which can be used for the purpose of calculating the theoretical response of any collecting device.

(ii) Theoretical studies of the fluid loading on structures in which part of the incident wave energy is absorbed, and of the basic engineering problems involved in the design of such structures.

(iii) Studies of mooring and anchoring problems.

(iv) Studies of methods of transmitting power to shore from remote wave energy collecting devices.

(c) To assess the possibility of:-

(i) An exchange of information between organisations in participating countries concerning the behaviour of specific devices in test locations.

(ii) developing joint programmes for larger-scale experiments under IEA auspices.

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DEPARTMENT OF INDUSTRY

NATIONAL ENGINEERING LABORATORY

THE DEVELOPMENT OF WAVE POWER - A TECHNO-ECONOMIC STUDY

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PART 1 - SUMMARY

This document summarises the main findings of a study undertaken by the National Engineering Laboratory and presented in full in Part 2.

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C O N T E N T S

1 THE SURVEY

In February 1974 NEL was formally asked by the Energy Technlogy Division of the Department of Energy to undertake a study of the economic and technical feasibility of large-scale generation of electricity in the UK from sea/ ocean waves. A preliminary study by the Department had concluded that the large-scale exploitation of wave power appeared to be technically feasible but that the cost of electricity produced would probably be around twice the cost of power generated by nuclear means. The NEL survey was commissioned to take a second and broader look at wave-powered generation in order to test the conclusions of the preliminary study.

The study, carried out by NEL's Economic Assessment Unit and Fluid Mechanics Division, obtained information from published sources and from visiting and contacting organisations and individuals concerned with wave-powered concepts, wave data and offshore operations. Details of work being undertaken abroad was obtained by UK Scientific Counsellors stationed in British Embassies in the USA, Europe and Japan.

During the course of the study considerable developments took place such as the award of the University of Edinburgh contract and the investigations undertaken by the CEGB and other organisations. The interest and the effort being expended by others must necessarily mean that the current situation in regard to wave power is a dynamic rather than a static one. Consequently, this study, although it has been able to produce a reasonably complete assessment regarding the state-of-the-art existing at one point in time, should be considered in the light of other work on the subject which has been undertaken since its inception.

2 THE NEED FOR WAVE POWER

In considering the development of wave power in the UK some of the possible reasons for making provision for an alternative and preferably inexhaustible source of energy were explored. We see the main factors in favour of alternative and preferably renewable sources (wind,solar, tidal, wave) as:

a Indigenous nature of renewable sources.

b Systems could be modular and decentralised and therefore less vulnerable to damage. Damage itself would not have seconary consequences.

c Systems are likely to be much less complex than nuclear systems and less demanding in the level of design, operation and maintenance skills required.

d Because of the possible limits to thermal pollution or on other grounds it may be desirable to determine that a certain percentage of a country's energy should be produced from renewable sources.

Having considered the alternative sources of energy available in the UK, we agree that wave power appears to be more attractive than wind or tidal power. In particular, wave power would appear to have the attraction of not requiring the very large single investments which tidal power would require.

3 WAVE DATA - THE ENERGY AVAILABLE

A vital part of this exercise was to confirm that the levels of energy in the sea waves around the coast of the UK are of sufficient magnitude to make wave power a genuine contender as an alternative source of power.

The energy in a train of sea waves can be calculated by considering the potential energy existing in the wave surface due to its deviation from a datum level. The power available can then be calculated by considering that this energy crosses a boundary at the wave velocity.

Based on this approach and using wave data obtained from the National Institute of Oceanography and from the National Physical Laboratory, mean annual power levels were calculated for various locations off the UK coast. The level of the power available is very sensitive to location. Off Lands End, for example, the mean power output was calculated to be around 27 kW/m whereas in the Atlantic off the Hebrides power levels can reach 70 kW/m.

A simple relationship between 50-year design waves and energy levels was deduced enabling maps of annual energy available to be built up. It was estimated that the wave energy on a 1700-mile contour 10 miles from the shore around Great Britain is around 500 million megawatt hours (equivalent to a mean power level of 21 kW/m). This is more than twice the combined annual energy output of the Electricity Boards in the UK.

Should wave power become a serious proposition there may have to be a reconsideration of navigational clearways; if allowance were made for existing recommended clearways it is estimated that the 1700 miles available would be reduced to 500-1000 miles depending on distance from the shore.

One of the attractive features of wave energy is that it is at a maximum in the winter when consumption is also at its highest. There is however a greater variation in wave energy available than energy demanded with the result that there would either be a shortfall of energy in the summer or a theoretical excess (over the maximum installed rating) in the winter.

No wave-power scheme can be conceived that would remove all of the energy in sea waves, nor would this be desirable, and it is therefore necessary to calculate what could be reasonably captured in practice. Assuming that a wave-power scheme were to occupy 50 per cent of the length of any contour and was then to be capable of converting 50 per cent of the wave energy to usable power gives an overall efficiency of 25 per cent. Using this figure of 25 per cent, half the total British requirements for electricity could be met by the wave energy in a stretch of ocean between 600 and 1400 miles long. The shorter length corresponds to all generation being undertaken at the best sites.

The best sites (Fig. 1) correspond to a line at variable distance from the shore and comprise 450 miles running parallel to the Outer Hebrides then turning east towards Orkney and north to Shetland, 45 miles of a line between Fraserburgh and Wick, 130 miles of the English Channel from Lizard Point to Portland Bill and 60 miles on a line approximately north-west of a point 10 miles west of the Isles of Scilly.

4 WAVE ENERGY WORLD WIDE

The levels of wave energy in the North Sea and off the south of England are roughly the same as the levels of energy off the USA, Canada, Japan and Australia. The Atlantic approaches of the British Isles, excluding south-west England, have however much higher wave energy levels and more constancy of wave direction than any other sea area in the world adjacent to areas of high energy consumption.

5 ENVIRONMENTAL ASSESSMENT

It is very difficult to assess at this stage the environmental effects of wave-power stations but it is clear that putting wave-power generating stations into UK waters in any significant numbers is likely to cause difficulties to existing fishing operations. There may however be benefits to be gained from the existence of floating structures which do, in themselves, tend to attract fish or which could be intentionally used for mariculture techniques. Floating structures could also be used to limit the access of vessels to certain areas and thus prevent overfishing particularly by foreign vessels.

The effect on the coastline of removing wave energy also cannot be easily assessed. There can be little doubt that removing all of the wave energy on a continuous line not far from shore would have a significant effect on coastal erosion, deposition and sea-water turbidity. To determine the magnitude of these effects and whether they would be beneficial or harmful would require specific studies of particular generating schemes at particular locations. It is unlikely however that any practical wave-power scheme would extract more than half of the total incoming wave energy.

Certain designs of wave-power generator may not be unsightly. In general, generating stations would most likely be sufficiently far off shore or of low enough profile not to have an adverse effect on visual amenity. Certain designs of stations could also provide positive recreational benefits such as fishing platforms.

6 ENGINEERING SCHEMES

Wave power is innovatory as far as serious investigation is concerned but is not a new concept. It is estimated that over 350 British patents were granted between 1856 and 1973 for devices which were claimed to be able to utilise sea wave energy.

A schematic diagram was devised to classify the various principles of operation embodied in past and current proposals and 38 system types were accommodated. A review of wave-powered generators built and tested to date was undertaken. Schemes can be classified according to how they appear to extract wave energy. The energy in water waves can be thought of in terms of:

a Variations in surface profile of travelling deep-water waves.

b Sub-surface pressure variations.

c Sub-surface fluid particle motion.

d Unidirection motion of fluid particles in a shallow-water wave.

Schemes in category (a) include the many proposals for floats utilising a drive operated by a mechanical link between the float and a sea bed or shore-based connection or even a larger floating structure. Other proposals utilise the relative motion of a column of fluid within the float structure and this has been utilised both directly and by employing the secondary movement of air. A further option is to generate electricity directly from the oscillatory linear motion of an armature within an annular stator.

The fluctuation in pressure below the water surface can also be utilised in a number of ways. Oscillation of a water column inside a vertical tube could drive a rotor on a vertical shaft. Using the water column to displace air and drive an air turbine was demonstrated as early as 1910 and is now the basis of a commercial unit. Also relying on sub-surface pressure variations is a concept being investigated by Kayser in Germany.

The easiest way to utilise the sub-surface motion of fluid particles is to hinge a simple vertical flap about its lower edge and then to tap its oscillatory motion. The low efficiencies inherent in this simple concept have been overcome by Salter who has demonstrated that efficiencies above 90 per cent can be achieved with an asymmetric vane.

A combination of sloping ramps and converging wave channels has been used with shoaling waves; this has been shown in the past to be technically feasible but not economically viable. Re-appraisal of this type of scheme now suggests the possibility of economic viability at specific locations(1).

7 CURRENT WAVE-POWER INVESTIGATIONS

Contrary to first impressions we found considerable and increasing activity in the UK and in other countries on wave power. Assessment and experimental work is being undertaken in the USA, France, Germany, Sweden, Finland and Japan. A list of all the organisations and individuals concerned with wave power is given in an Appendix to the full report.

8 SELECTION OF WAVE-POWERED GENERATORS

The attributes of a generator, in the absence of actual experience of operating such machines, have to be chosen on the basis of informed opinion. In selecting schemes worthy of further study the test criteria applied were:

i Number of intermediate stages between wave energy and electrical output.

ii Primary efficiency, wave/mechanical.

iii Linkage complexity.

iv Degree of stress concentration in principal components.

v Extent of exposure of components to sea water.

vi Manufacturing complexity.

vii Difficulty of transportation between manufacturing site and operating site.

viii Complexity of maintenance and repair.

ix Extent of hazard presented to navigation and fishing.

x Likelihood of damage to system if required to produce power in severe sea conditions.

xi Sensitivity of output to wave height.

xii Sensitivity of output to wave length.

xiii Difficulty of achieving tidal compensation.

xiv Possibility of extracting energy from more than one direction simultaneously.

xv Possibility of realigning structure to suit principal wave direction.

xvi Likelihood of adverse criticism on credibility and aesthetic considerations.

xvii Extent of R & D effort required to produce a prototype.

Applying these criteria, three promising schemes, the 'front-runners', were selected as worthy of further assessment. These are the floating ring buoy concept described by Masuda(2), the oscillating vane device of Salter(3) and the diaphragm buoy of Kayser(4).

In the ring buoy, shown in Fig. 2, the oscillation of the water level in an open-bottomed chamber results in a displacement of air which is rectified by a flap valve arrangement and used to drive an air turbine. Salter's device (Fig. 3) employs an asymmetric vane which oscillates in response to the incoming wave train and could be used to provide high-pressure fluid to a hydraulic motor or turbine. Kayser's device, shown in Fig. 4 in a buoy embodiment, utilises sub-surface pressure variations to operate a piston eventually powering a hydraulic turbine.

9 THE MOST PROMISING SCHEME

We selected the floating ring buoy scheme of Masuda for further technical and economic assessment. At the time of selection this particular scheme appeared to satisfy all the criteria which we postulated and it also appeared to be of such construction that its cost could be readily estimated. Having undertaken the assessment it was found that this thesis was partly justified but that considerable uncertainties on the technical design still remained. Consequently, we still rate this scheme as one of the 'front-runners' but it would be pretentious to claim that it, and it alone, merits the title of 'most promising scheme'. Moreover, the costs estimated for the scheme are inevitably based on untested technical assumptions about its operation and therefore these costs should be viewed with this firmly in mind.

The particular merits which led us to select this system for further assessment were:

a No large external moving parts.

b High efficiency claimed for wave to air energy conversion from tests carried out on floating breakwaters and rigidly held chambers.

c The valved air turbine/a.c. generator system has already been demonstrated to be effective and reliable in small units operating in the marine environment over a number of years.

d Fabrication of floating ring buoys could be undertaken using existing shipbuilding and construction technology.

e Overall system has a higher credibility rating than most others and could well lend itself to multiple-use applications.

On the other hand, this system shares the same areas of uncertainty as other wave-power generators namely:

a Motion of the structure in real sea conditions.

b Forces exerted by wind, current and waves on the structure.

c Structural design and mooring requirements.

d Arrangements for collecting power from a number of stations and transmission back to shore.

Uncertainties peculiar to this particular scheme are likely to be:

a Air displacement pattern within each chamber in real sea conditions.

b Optimisation of valve/air turbine/generator parameters.

c Harnessing the output from a large number of generators or integrating a large number of air flows to an air turbine.

10 COST OF WAVE-POWER GENERATION

With no provision for back-up it is estimated that the floating ring buoy concept, including transmission to shore, could cost from £700-1400/kW (equivalent to unity load factor) or more meaningfully could produce electricity at about 1p/kW h annuitised at 10 per cent. No undue emphasis should be placed on these cost estimates as the assessment did not and could not determine the costs of structures and components whose detailed design requires extensive investigation.

Cost estimates for wave-power generation made by other studies and investigations in the past were converted to today's prices giving capital costs at various or unknown load factors in the range £175-350/kW. Calculating capital costs at unity load factor, where possible, gives a range of £300-600/kW.

The estimates produced by this study and others indicate that wave-generated electricity is likely to be more expensive than nuclear-generated electricity but possibly by no more than a factor of 3, not by an order of magnitude. Without further design and development work it is not possible to be more precise than this. In suggesting the need for further development it must be emphasised that one function of R & D is to provide the information required to take major capital investment decisions. Further work to determine the economics of wave power could decide in which of three categories wave-powered generation lay:

a Capital cost less than nuclear plant and therefore justified on economic grounds alone.

b Capital costs higher than nuclear power but the additional cost balanced by benefits based on strategic considerations or multiple use of offshore platforms.

c Capital costs so much higher than nuclear that the additional cost far outweighs any conceivable summation of benefits.

11 MANUFACTURE OF WAVE-POWER STATIONS

In examining the potential of wave power to satisfy the demands of an alternative power source it is considered that large-scale production of energy from sea waves is technically feasible and could be achieved by the development of existing technology.

The construction of wave-power stations would be able to utilise the manufacturing technology and facilities which continue to be developed for exploration and production of oil in UK waters. Production of wave-power stations would however compete for resources if it were to be undertaken on any significant scale before the demand for oil platforms and equipment slows down. If on the other hand the two programmes were inter-phased there is a possibility of prolonging the life of offshore engineering activities in the UK.

There is a current trend for industry (power generation, chemical and mineral processing) and other activities to be moving into the offshore environment. Wave-power generation must be viewed in this context and opportunities will arise to make multiple use of floating platforms thus radically improving the credibility and economics of wave-power generation.

12 THE DEVELOPMENT OF WAVE POWER IN THE UK - RECOMMENDATIONS

In our main report we discuss in detail the various options for the further development of wave power in terms of low, medium and high profile responses.

Our main recommendations are:

a The UK should maintain an interest in the development of power generation from sea-wave energy.

b Liaison should be established and maintained between all centres in the UK and elsewhere which are concerned with the development and applications of wave power.

c The research programme on wave power at Edinburgh University should receive continuing support within the terms already laid down.

d Consideration should be given to a programme of work complementary to the Edinburgh programme to investigate means of converting oscillating mechanical motion into a usable form of energy.

e Consideration should also be given to design/development studies of a system or systems other than that being developed at Edinburgh University. Systems based on the displacement of air to drive an air turbine are considered to be the most promising alternatives.

f All competing wave-power schemes in the UK and abroad should be assessed against each other as further information becomes available. Wave power schemes should be continually assessed against other alternative sources such as wind and tidal schemes.

g The effect on specific sections of the coastline of installing particular configurations of wave absorbing devices should be studied by experts competent in that field.

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LIST OF FIGURES

FIG. 1 THE BEST AREAS FOR USE

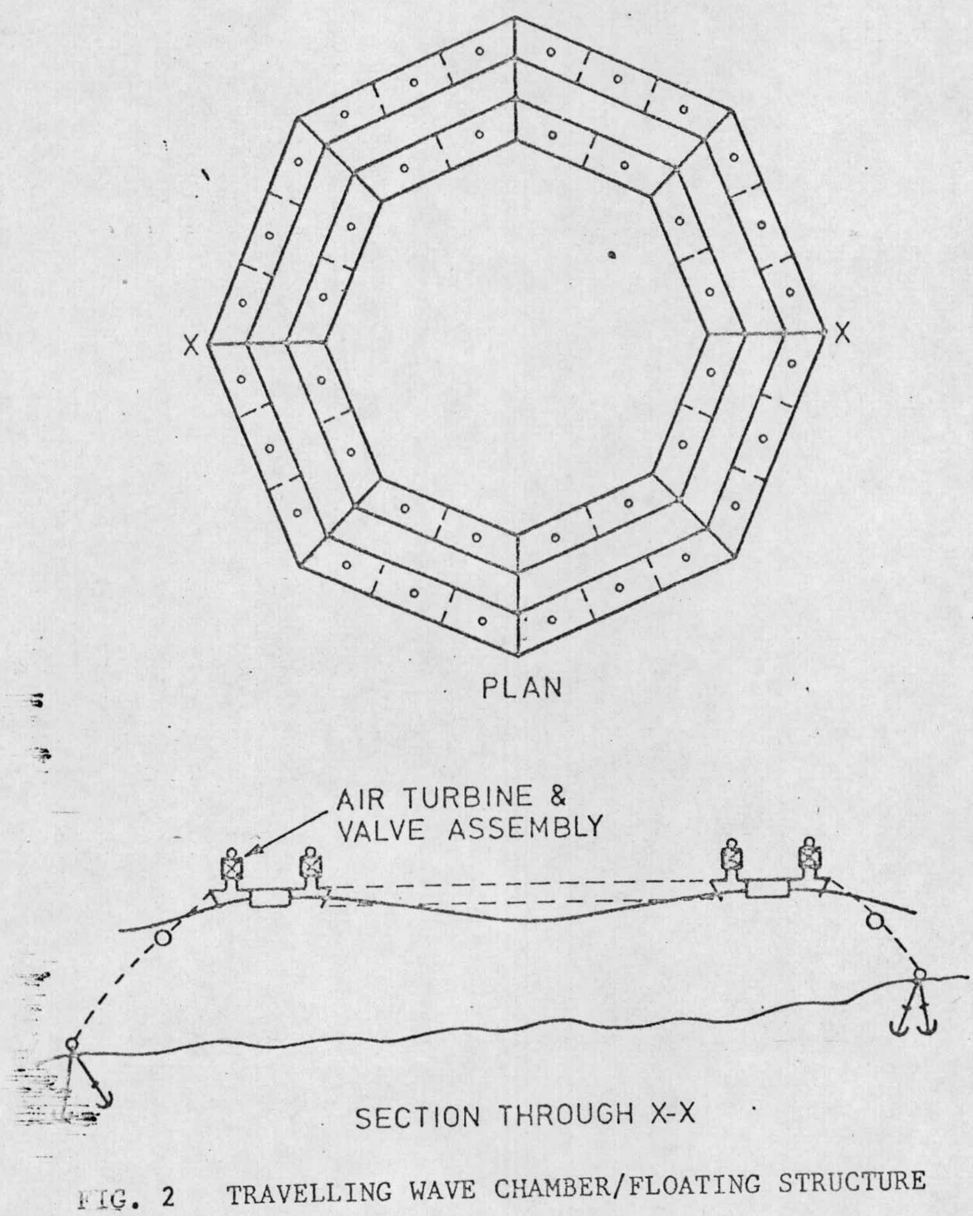

FIG. 2 TRAVELLING WAVE CHAMBER/FLOATING STRUCTURE

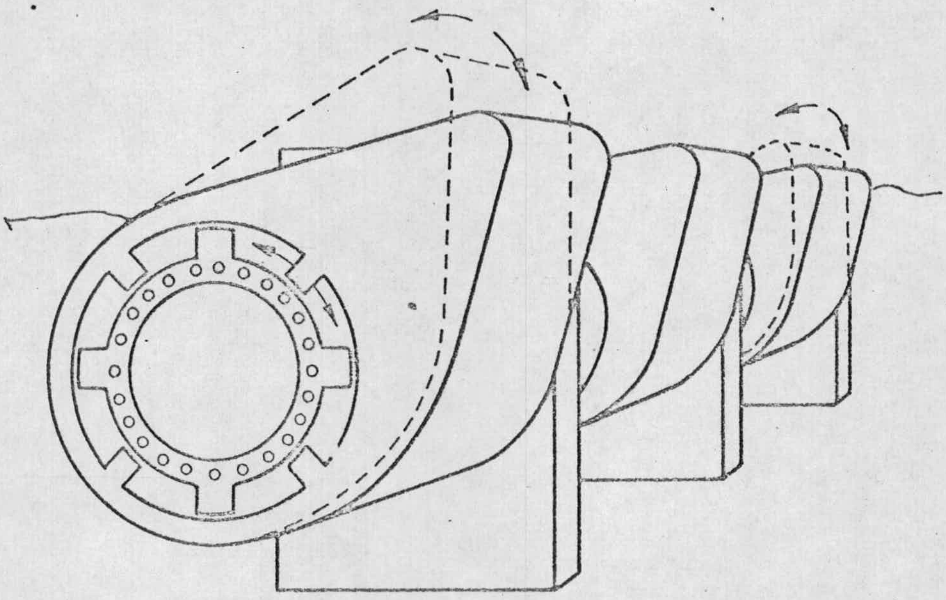

FIG 3 OSCILLATING VANE/FLOATING STRUCTURE

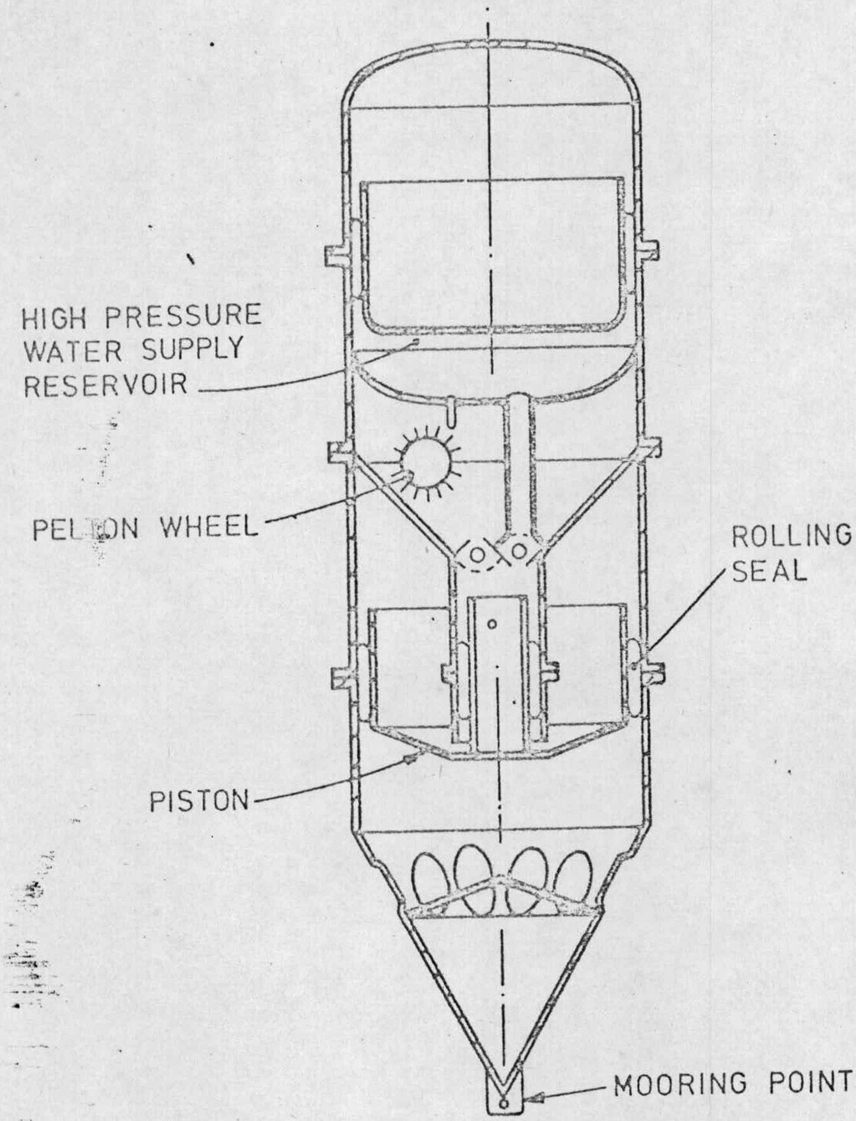

FIG. 4 TAUT LINE BUOY/PISTON OPERATION

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Ref 2

The architecture of nodding duck wave power generators

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RECENT CHANGES in attitudes to energy supplies have stimulated interest in sea waves as an alternative energy source. The performance of tank models of several varieties (1–5) has been promising enough to justify support for serious work. The technology draws heavily on the work of naval architects and may lead the subject into new areas. This article describes one of the techniques.

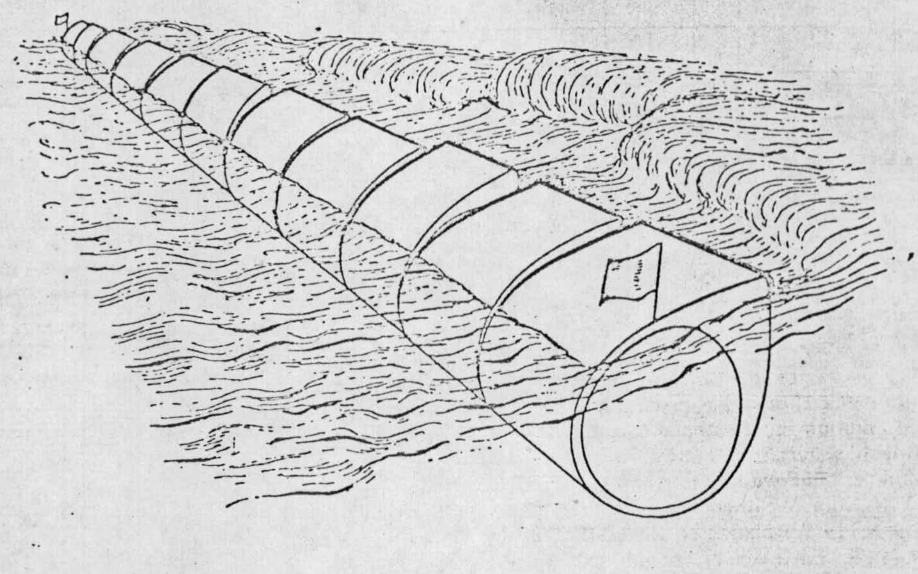

Fig 1. Artist's impression of full-scale equipment at sea.

Our equipment consists of a tubular backbone some 500 metres long, around which can rotate a number of peculiarly shaped segments known as 'ducks'. An impression of what this equipment might look like at sea is given in Fig 1. The reason for the choice of the term 'duck' is not entirely frivolous; new ideas need new names and it is as well to keep them short and descriptive. The combination of ducks and backbone is called a 'string'. It will generally lie parallel to the crests of the waves. Movements of the backbone can be named directly from conventional rigid ship usage, but it is necessary to coin a new name for the seventh degree of freedom of the duck relative to the backbone. The term 'nod' is winning rapid acceptance. It has been used by an aircraft manufacturer with a preference for compliant engine mountings.

It is also necessary to define orientation. As ships are usually symmetrical port and starboard but dissimilar fore and aft and we would like the ducks to face oncoming waves, we argue that the length of the string corresponds to the beam of a ship so that pitch and nod occur about parallel axes.

The most elementary calculations show that in some sea conditions the backbone will be subjected to enormous bending moments which rise with the square of length. It would probably not be economic to attempt to resist them with rigid thinking and construction. Our colleague, Eric Wood, has produced an elegant design which is rigid for low bending moments but which becomes flexible before damage can occur. In addition to hog and sag we have to consider deflections in the horizontal plane. We propose the words 'give' and 'take'. The string gives to leeward and takes to waveward.

The gaps between ducks allow access to the backbone for the attachment of mooring lines and power cables. They also allow for fitting appendages like outboard bilge keels below and behind the string. But at present we hope to obtain all the stability necessary for the backbone from the fact that it will sample a variety of phases of wave along its length. We would put the effort and money into making the backbone long and strong.

The duck strings will be loosely moored at sites with consistently good waves as close to shore as possible in 30 to 50 fathoms of water. The problems of mooring have been greatly reduced by the work of ICI on 'Parafil' ropes(6).

These duck strings will generate electricity out at sea. The value of a unit of wave-generated electricity is set by the value of the oil it saves in generation. In November 1975 this was 1·1p.

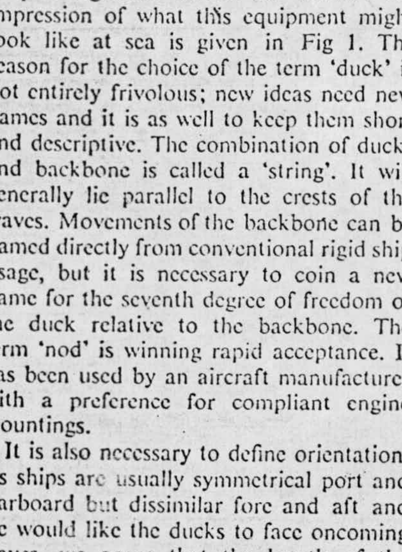

Fig 2. Year-round scatter diagram for the weather ship 'India'. Each entry in the table shows the probability in parts per thousand of a particular combination of significant wave height and zero-crossing period.

Power take-off

The nodding of the duck about its axis will produce useful work. It will usually have an angular amplitude of less than half a radian. The peripheral velocities between duck and backbone are too slow by two orders of magnitude for conventional electricity generation. But there are commercially available a rich variety of hydrostatic rotary transmission components(7) which are very efficient as both motors and pumps.

Radial piston units such as those produced by Poclain and McTaggart Scott can provide radial and axial location as well as power take-off. They are used as wheel hub motors for slow heavy vehicles and have large axle load ratings. Each duck will ride on as many as 100 of these which are fitted with seals for marine and submarine applications. They will produce a flow of hydraulic oil at pressures of 2–3 000 lb/in^2. This is now a high grade form of energy. It can be used to drive hydraulic swash plate motors(7) at speeds compatible with electrical generation. Control of the angle of a swash plate allows the generator to run at a constant speed despite the periodicity of the duck nods.

The simplest possible control system, easy to implement and analyse, would make the force between duck and backbone proportional to velocity. The constant of proportionality affects efficiency but it is not desperately critical either side of the optimum. Change by a factor of two reduces efficiency by only 15%. We have built circuitry which can simulate many other types of power take-off. A steady force of polarity opposite to duck backbone velocity is effective provided it is of the right magnitude. It is also possible to take power on only half the cycle with a loss of less than 5%.

A more sophisticated control unit processes the velocity signals in a network which produces gain and phase changes for different frequencies. This cancels to some extent the reactive components of the duck and produces a substantial widening of the

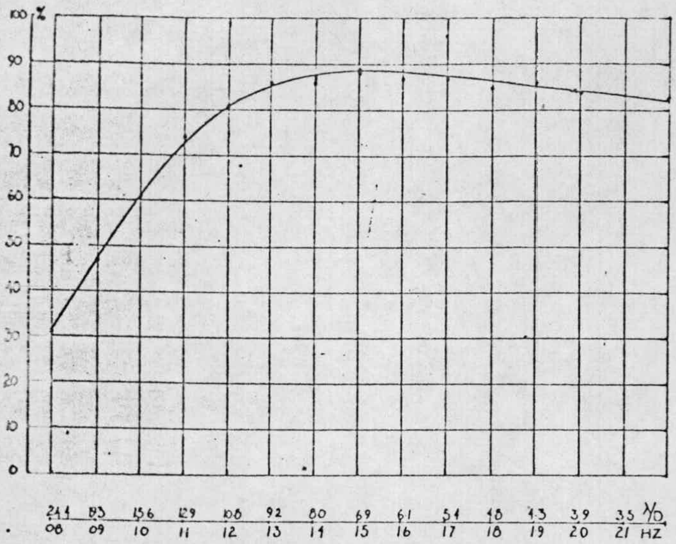

Fig 3. Efficiency curve for 100 mm model on fixed bearings with sinusoidal waves of moderate amplitude.

efficiency band. It can be implemented in the full scale hydraulic control.

Power levels

The work of the Institute of Oceanographic Sciences[8] has produced very good information about the wave climate in British waters. Fig 2 shows a year-round summer and winter diagram of observations from Weather Ship Station 'India' (59°N, 19°W) characteristic of the North Atlantic. Each cell of the table shows the occurrence in parts per thousand of a particular combination of significant wave height and zero crossing period. Isodynes, lines of constant power density, are superimposed.

For quick mental calculations it is useful to remember that the properties of the MKS system are such that in a sinusoidal train of waves the product of the square of trough-crest height in metres and the period in seconds is very nearly the power density in kilowatts per metre. The mixture of heights of waves found at sea is described by the 'significant wave height' and the power density is nearly one half of the period multiplied by the square of the significant wave height.

Mollison has performed a rigorous analysis of wave spectra[9] produced by Hoffman[10] from IOS data. He found that the average North Atlantic power density is 93 kW/m but that this would only be accessible to a zig-zag array of duck strings. If directional corrections are made, the figure reduces to 80 kW/m for a straight string. Model ducks on a fixed axis have produced efficiencies in the nineties for sinusoidal waves. We are considering ways to throw some of this efficiency away to give cheaper installations. Fig 3 shows the preferred curve at September 1975. It shows a 2 : 1 frequency bandwidth in the eighties with a fall to 50% for a wave length 18 times the duck diameter.

It is sometimes said that optimum efficiencies should be between 60 and 70%. A poll of leading wave theoreticians produced average expected mean efficiency of 66·7% for wave machines. Mollison has superimposed the curve of Fig 3 on to a representative sample of wave spectra and applied a set of power cut-off limits. A 14-m diameter duck limited to 200 kW/m will get 50 kW/m over the year. He has shown that Salter's estimate that good wave machines should get all the energy in their draught band and none below was somewhat conservative for wave-to-duck efficiency but perhaps a reasonable guess if conversion and transmission are taken into account.

The shape of the duck

Fig 4 shows a duck mounted on its backbone in calm water expecting waves from the right. It will nod about the point O. The flat part of the duck out of the water is called the back; the highest point is the beak; the curve down from the beak is the paunch and the remaining semicircle is called, for reasons of delicacy, the stern.

The simplest designs will have the stern of the duck in the shape of a cylinder coaxial with the nodding axis so that nodding will not displace water astern. The diameter of this cylinder is the dimension used to describe the size of the duck. For the North Atlantic it will be between 10 and 15 metres, but for shorter waves in the North Sea or western Japanese waters it may be as little as 6 metres.

The curve of the paunch is designed to allow the displacements of water in front of the duck, caused by a nod, to match as nearly as possible the sizes of the orbits of the water particles in an approaching wave of period at which best performance is required. The matching can only be approximate but quite large departures cause only a small difference.

Consider the line in Fig 5 whose ends are distant from O by R and R + dR. As the line moves round O it sweeps out an area ØRdR. It is well known[11] that in a deep

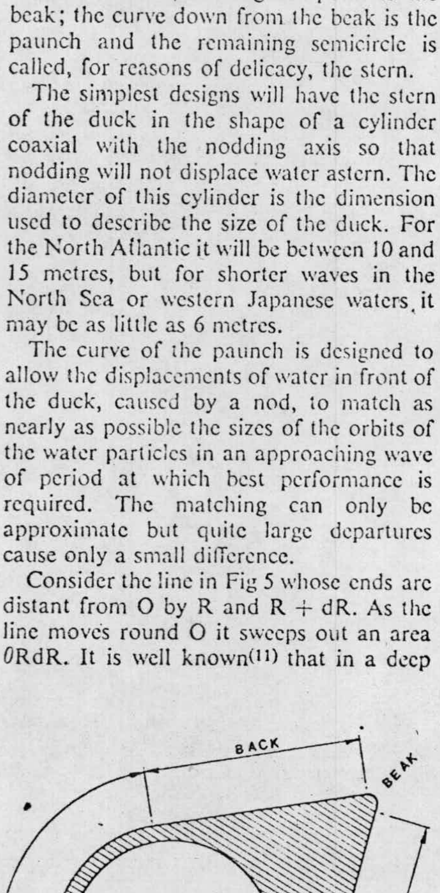

Fig 4. Anatomy of a duck.

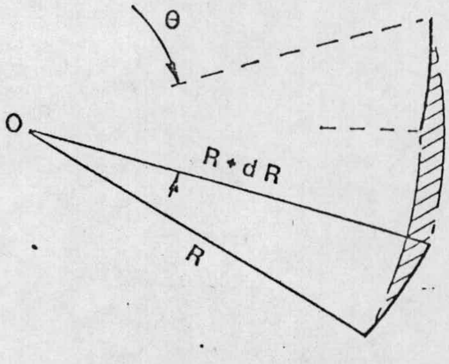

Fig 5. Area (ØRdR) swept out by a line.

water travelling wave with surface amplitude A and wave length λ the radius of orbit at a depth Z is $Ae^{-2\pi Z/\lambda}$. We can derive an equation for the paunch radius R at any depth Z

$$R = Ke^{-2\pi Z/\lambda}$$

and fix the value of K for Z = 2R for some ratio of λ/R. The curve for $\lambda/R = 20$ is shown in Fig 6. For convenience of marking out in the workshop, our early models were made with the combination of an arc and tangent, shown dashed.

The duck freeboard is the distance from the beak to the calm waterline. It can be used as the first stage of overload protection. The phase of nodding is such that for a wave in the middle of the working band the duck is at its calm water position as a crest arrives. Waves of amplitude greater than the freeboard will send water over the duck and so the freeboard dimension should be chosen to suit hydraulic and electrical overload limits. In the North Atlantic the economic power limits will be between 100 and 200 kW/m.

Flow of water across the duck's back has important implications in connection with mooring and drift forces. Longuet-Higgins[12] has shown that a perfect wave absorber should experience a direct beachward force in addition to all alternating forces and those caused by currents. In waves of amplitude A it should have the value

$$\tfrac{1}{4}\rho g A^2 \quad \text{per unit length.}$$

A reflecting object would experience a force of double this value. Our model mounting is fitted with strain gauges and the force signals can be put through low-pass filters. Experiment confirms theory up to the point where water goes over the duck. When this happens a head of water builds up behind the model and offsets to an appreciable extent the effects of the beachward forces. If this head is considered part of a transmitted wave then the prediction is still good.

We have tested a circular cylinder held just awash across the tank. It should be nearly transparent to the waves and so it is. But the average of the forces on it shows a forward component. It is possible to siphon water from back to front, and when released, the model will move slowly but surely towards the wave maker. To summarise then, low freeboard gives automatic power limiting and easy mooring.

The largest direct effect is a force vertically down, often eight times larger than the static horizontal force. Nautical tradition requires that conventional ships should

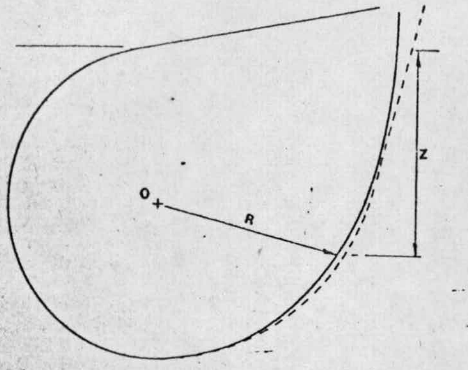

Fig 6. Paunch curves.

stay on the surface in more or less the same attitude at all times, but unmanned wave machines threatened with excessive wave forces will be much safer below the surface. We had planned a mooring scheme with a leading buoy designed to sink the duck string in very rough weather. It seems that the waves and Bernoulli will save us the trouble.

The stable position for an object floating in waves is perpendicular lengthwise to the prevailing wave direction. But it is possible to make use of the unidirectional forces for yaw control. By altering the hydraulic systems at one end of the string we can increase the amount of wave energy reflected and so move that end of the string down-wave.

In calm water the duck will lie as in Fig 7. It will experience an upwards buoyancy force $\nabla\rho g$ at the centroid of the displaced water and a downward force from its own centre of mass at W. It is not necessary that $\nabla\rho$ and M should be equal. We might decide, for example, that if a duck were to become detached it would be better for it to sink rather than to float about causing damage to its siblings. The backbone would provide the reserve buoyancy. The only requirement is for $\nabla\rho g$ and Mg to exert equal but opposite moments about O. The point of action of $\nabla\rho g$ is fixed by the duck shape but the position of W can be controlled by the distribution of material inside the duck. Ducks and ships differ in that the duck's centre of gravity will be placed as high as possible.

It is not surprising to find that ducks perform best at their undamped natural frequency. This frequency will be given by

$$F = \frac{1}{2\pi}\sqrt{\left(\frac{\text{Stiffness}}{\text{Inertia}}\right)}.$$

There are two factors affecting stiffness. The first is governed by the waterline length L in Fig. 7. A small clockwise nod of angle $d\theta$ will displace a triangular prism of water of volume

$$\tfrac{1}{2}L^2 d\theta \quad \text{per unit length of duck.}$$

This will have a mass

$$\tfrac{1}{2}\rho L^2 d\theta$$

and a centroid at $\tfrac{2}{3}$ L from the vertical through O.
The change of moment about O will be

$$\tfrac{1}{3}\rho g L^3 d\theta \quad \text{anti-clockwise}$$

and so the rate of change of moment with angle will be

$$\tfrac{1}{3}\rho g L^3.$$

For large nod angles the problem is complicated by change in the value of L. But we only require optimum efficiency for small nod angles. Nodding stiffness is also affected by the position of the centre of mass W. If this is a distance of C from O and the line OW makes an angle ϕ with the vertical, then the moment about O is MgC sin ϕ. Differentiating gives MgC cos ϕ. When ϕ is acute then the move in the centre of mass tends to assist the nod which caused it and so the sum of the stiffness terms is

$$\tfrac{1}{3}\rho g L^3 - MgC\cos\theta \text{ per unit length.}$$

There are several terms which affect the nodding inertia. There is the obvious mechanical moment of inertia of steel and concrete. This is the sum of the products of the mass of each small part and the square of its distance from O. There is the inertia of the power take-off hydraulic pumps which may be turning 20 times faster than the ducks. There is also the hydrodynamic inertia of the water influenced by the duck. Values for this have been calculated for some shapes and measured for others. Fig 8 shows the values for some shapes. If we consider the circle to be a special case of ellipse which happens to have a = b, and the plate to be another special case where a = 0, then we see a gratifying consistency. If you pressed a naval architect to tell you the value of added hydrodynamic inertia for the duck, he might argue that the active parts resemble a quadrant of an ellipse and suggest the value

$$\frac{1}{32}\pi\rho(b^2 - a^2)^2$$

But while books on naval architecture talk of *the* added inertia in the singular, the wave theoreticians believe that it is frequency-dependent. Model measurements using a 'twinge' test, in which a pulse of torque is applied and the velocity after a short interval is noted, are not good predictors of natural nodding frequency. A technique which plots the velocity response

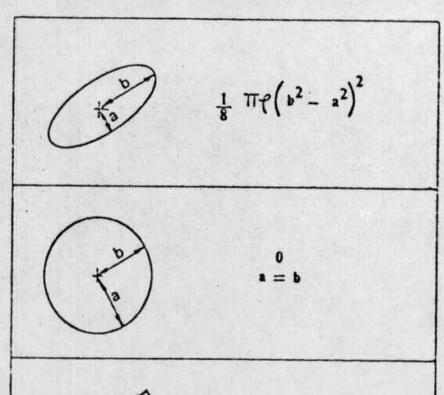

Fig 8. Hydrodynamic moments of inertia for some shapes.

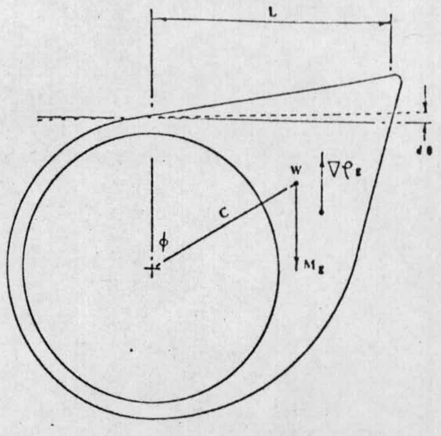

Fig 7. Duck forces.

to sinusoidal excitation over the frequency range is good but tedious and requires much attention to the design of wave-absorbing beaches. All three forced-response methods are unsatisfactory and some fresh approach to the problem is needed. One feels that the hydrodynamic inertia should be a minimum at the wave length which best suits the paunch curve. Until then we may use the expression

$$F = \frac{1}{2\pi}\sqrt{\left[\frac{\tfrac{1}{3}\rho g L^3 - MgC\cos\phi}{I\ \text{mech} + \tfrac{1}{32}\pi\rho(b^2 - a^2)^2}\right]}.$$

When the duck is driven at its natural frequency the effects of stiffness and inertia cancel and the response is solely determined by the damping. This is largely the power take-off. When it is optimum the efficiency can be extremely high. If damping is increased then waves are reflected in such a phase as to produce an anti-node at the beak. When the damping is below optimum then again there is reflection but with a node at the beak. The transmitted wave is not much affected by the value of damping. The calmness of the water behind the duck string may have some commercial value but is no greater than that from a passive object of similar draught. A passive object would be subjected to forces twice that of an active duck.

When the duck is driven by waves at frequencies different from the natural frequency then its behaviour is governed by stiffness at low frequencies and inertia at high frequencies. To make the operating band wide we require the stiffness and inertia values low in relation to the damping. In electronic terms we require a low Q. The design procedure is as follows. The first component of the stiffness is determined by the waterline geometry. As much as possible of this is cancelled by reducing the angle ϕ by raising the centre of mass. The limit to this is the requirement that the duck should recover from a capsized position. We believe that this should be a natural recovery unassisted by reverse operation of the pumps. The inertia is then set to bring the remaining stiffness into resonance at the required frequency. Fortunately, the bandwidth required is not wide. For many sites the bulk of useful energy through the year is concentrated in half an octave. A mechanism which altered the operating frequency by, say, pumping ballast between compartments in the duck would have to be very cheap to be considered.

Where really wide band performance is

needed, it is possible in the laboratory to build very low-inertia ducks, to sink them with force from a negative rate spring and to cancel residual stiffness and inertia with signals to an electric motor. This produces a mechanism (UK Patent application No 34546/75) which serves as an admirable wave maker, insensitive to reflections from models in the tank. It can produce very stable test conditions, short tank settling times, and even stable standing waves.

Conclusions

Extrapolations from model to prototype are fraught with pitfalls. But most duck behaviour is determined by inertial forces and they allow the safest extrapolation. Viscous losses will be proportionally higher in models and so there will be a small bonus for the prototypes.

Tank work with fixed axis models is drawing to a close. We now have to make ducks work from a water reference and find out how to control floating strings of variable flexibility in seas of various lengths.

The model builders will produce curves which show how output falls with low rigidity for different wave conditions. The structure designers will produce curves which show how cost rises with high rigidity. The wave theoreticians and observers will tell us which conditions will occur. (The statistics of crest length are particularly important.) The accountants will tell us the prices of steel, concrete, parafil, transmission cable, electro-hydraulic machinery and labour. We will try to think of all the objections and difficulties[13] such as fouling, fatigue, and storms, wave ownership and navigational hazard—objections which can mostly be raised against ships themselves. And then perhaps we will build our full-scale duck strings and send them to be tested by the sea.

ACKNOWLEDGEMENT

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Ref 3

Energy on the crest of a wave

Wavepower could be Britain's contribution to the repertoire of unconventional energy systems. A private company is working on a simple system that could be built up from small and inexpensive modules

Malcolm Woolley and **Jim Platts** are engineers at Wavepower Limited of Southampton

Wavepower came to be discussed as an interesting, possibly economic, source of energy for Britain during 1974. The Central Policy Review Staff report on energy conservation first mentioned wavepower in July. Following that, a paper study was commissioned from the National Engineering Laboratories at East Kilbride. Stephen Salter at Edinburgh University aroused more interest with a paper in Nature (vol 249, p 722). The Department of Trade and Industry subsequently set aside £65 000 for a three year laboratory research programme at Edinburgh University which is now under way (see Energy file, New Scientist, vol 64, p 503). The Central Electricity Generating Board has shown an interest in assessing wave energy as a source of electrical power: it has completed some theoretical analyses and has started laboratory work (see Nature, vol 254, p 504).

Sir Christopher Cockerell's interest in wave energy began in 1972 when he made the kind of calculations on energy availability that are now familiarly quoted. Early in 1974, Wavepower Limited was formed by Cockerell and Edwin Gifford of Gifford and Partners, consulting engineers. The company set out to study various wavepower devices and to prepare the ground for the commercial development of wave energy systems. British Hovercraft Corporation has conducted some tank tests for Wavepower Limited, studying various simple float systems.

If wavepower were the only sort of energy available, its inherent variability from day to day, and season to season, would be a problem. However, wave energy could be used in conjunction with thermal stations to provide sufficient capacity when wave power was low. Compared with other permanent sources of energy—the wind, for example—wavepower has a high availablity: there are always waves arriving around Britain from winds somewhere in the Atlantic. Power availability plotted against time follows an exponential curve as shown in Figure 1. In designing a wave energy machine, strength, size, and cost vary in relation to the peak output. A large, strong machine, typified by a line "A" in Figure 1, will extract almost al[l] the total energy available in a year but wil[l] be under-utilised for most of the time. A more modest machine, typified by line "B" in Figure 1, will generate its full quota o[f] energy most of the time, leaving only the shaded area "C" to be provided by standby thermal stations.

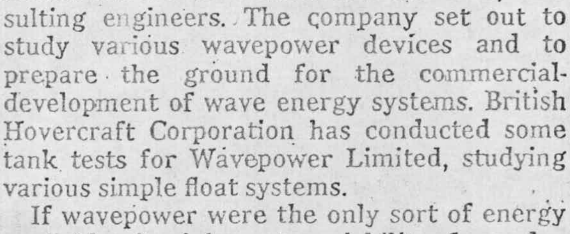


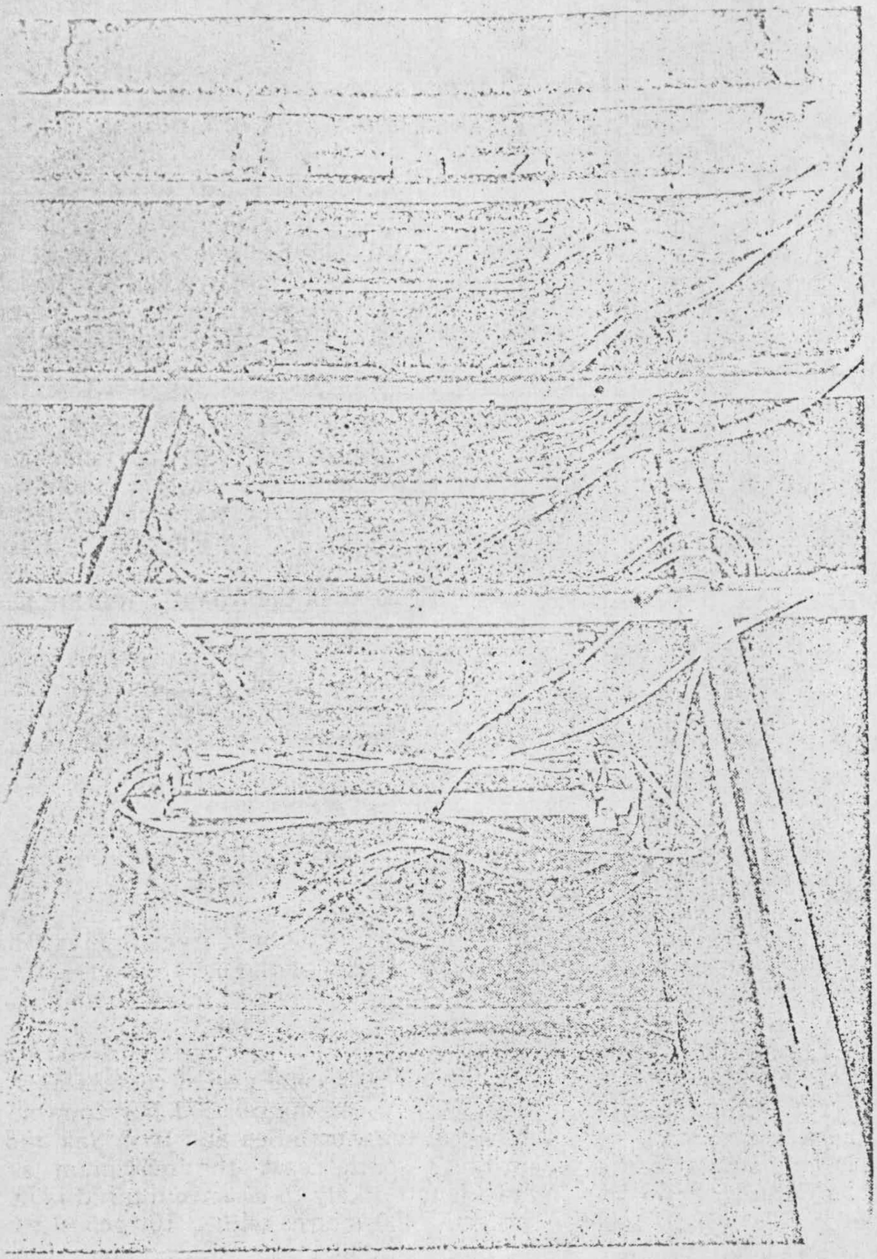
Figure 1 The amount of power available in the waves around Britain. The most powerful waves are the least frequent. Thus a device designed to make the most of these conditions (typified by line A) would be under-utilised most of the time. A wavepower device designed to more modest levels (as in line B) would generate its maximum output for most of the time

Public debate has concentrated on the high specific powers and high mechanica[l] efficiencies of particular locations and devices. The true criterion for wave power development should be the power produced for a given capital outlay. While there is immense power available in the Atlantic, it is not necessarily economic to tap it. Power in the North Sea, for example, is contained in a comparatively narrow band of wavelengths; and the machine designed to suit them may well be more efficient, in terms of capital cost per kW output, than a bigger device to cover the wider spread and larger waves in the Atlantic approaches. Also, although wave lengths diminish in shallow water, their steepness increases, and refraction effects tend to align the waves to the shore. This may enable a fixed device to be built free from the directional variability of the open ocean—a factor which could have important economic consequences.

In the Atlantic, storm waves of 600 metre length and 20 second period contain as much as 1500 kW per metre (600 horsepower per foot); in the North Sea and Irish Sea and on Britain's south coast, the maximum storm wavelength likely to be encountered is in the order of 400 metres with a 16 second period and a maximum power content approximately 700 kW (300 hp/ft). Even if a particular device was not designed to extract all this energy, it would have to survive such storm conditions.

Stephen Salter's rocking boom concept has had more publicity recently than other systems. Laboratory tests show great promise of a device with a basic efficiency of more than 50 per cent over an adequate range of wave lengths to cover the variable sea conditions around Britain's coastline. However, the rocking boom concept, as currently formulated, raises various practical questions which suggest that we can expect the designs to change considerably in the transition from laboratory theory to full size practice.

Wavepower Limited aims to develop a wavepower device that, within the bounds of current technology, is simple, cheap, made up of relatively small mass-produced units, can be installed in sections, and can be easily maintained a section at a time. This led us to investigate a chain of floats, hinged together, with waves travelling down the chain (see photograph). Pumps on the hinges absorb power from the relative rotation of adjacent floats. Tests indicate energy efficien-



...ure 2 Wavepower ...'s concept of a ...ve-contouring raft ...s been tried out in ...odel tests at the British ...overcraft Corporations' ...st tanks

cies of the same order as those obtained by Salter's rocking boom, but what matters is a comparative assessment of cost-efficiencies. Simple estimates are encouraging but more detailed work is needed before a sound judgement can be made.

In terms of scale, the individual size of float relates to the smallest waves it experiences rather than the largest. Floats longer than about a quarter of a wavelength would lose efficiency rapidly. For Atlantic conditions, floats corresponding to a quarter of the wavelength of the shortest waves (period 5 s and length 14 m) would be 10 m long. Similarly the width of floats is related to the minimum wave width rather than the maximum wave width. Floats might be 20 m to 40 m wide. Large ocean waves contain a lot of energy, but most of the power throughout the year is carried in the smaller waves. Thus an economically optimum design would not extract full power from very large waves.

To assemble these floats into an array is more complicated than the simple chain linking that has been used in the tank tests. However, Wavepower has established the principle of floats, hinges, and pumps of reasonable size. All the parts of such a device, even of a full ocean scale, are well within current technology, and we believe that a system of floats could be developed relatively quickly. All the components can be mass-produced, which makes a considerable difference to cost. These can be built up in parts as required or as finance permits, and all parts are accessible from above for maintenance. Any float can be removed and replaced by a temporary bridging piece. The loads on each float are not excessive and we believe that float systems have as much promise as other systems currently being discussed.

Wavepower for industry, too

Direct generation of electricity is the most obvious foreseeable application of wave power in Britain; but the direct industrial application of wavepower and its export potential is of considerable significance. The philosophy behind the direct industrial use of wave energy is that the power variability can be "smoothed" by making at a variable rate and storing the product. This may be valuable in underdeveloped countries, where standby generating capacity is not available. Pump-storage schemes can smooth supply requirements for hour-to-hour demand fluctuations, but wavepower has a seasonal fluctuation. There is also a considerable variation of generated power on a day by day and week by week basis. Large-scale storage of electrical power may involve the creation of large and expensive high-level water reservoirs. It is, therefore, worth investigating other methods of storing variable power output, such as manufacturing aluminium, hydrogen, or mineral extraction, and desalination processes.

The aluminium smelting rate, for example, can be varied to accommodate fluctuations in energy availability. The minimum requirement is enough energy to keep the furnaces up to temperature. Similarly, hydrogen can be produced and stored, or used in a chemical process and the product stored. The Central Electricity Generating Board (CEGB) has looked into the possibility of extracting uranium from sea water; other minerals can also be extracted from the sea. Desalination is also a possible application.

Hydrogen might, in the longer term, be used as an energy source and stored in disused natural gas fields. The economies of hydrogen production are difficult to assess as it is mainly produced and consumed within the chemical industry. The electrolytic production of hydrogen is now under considerable development. The direct use of electrolytic hydrogen in the production of ammonia for fertiliser is more relevant to today, particularly when export markets are considered. Large areas of the world are short of both energy and fertiliser. A wave-powered fertiliser plant may be able to produce useful quantities of fertiliser.

A successful wavepower device might also be a very effective breakwater. Floating breakwaters have been under investigation for some time, but they have so far proved too expensive. If power could be derived from a breakwater, it might make a material difference to the economics of some schemes, even though a wavepower/breakwater system would cost more to build. There are difficulties with such schemes; for example, the silting problems associated with floating breakwaters would apply to wavepower devices. Also, unless the breakwater reflects the energy it cannot use, extremely large waves could pass the device with considerable remaining amplitude and power.

Almost all coastlines have access to considerable wave energy. Though there are obvious differences in any given location, an argument for using waves as a power source on the eastern edge of the Atlantic is, broadly speaking, an argument that can be applied to the edges of all the oceans. Similarly an argument that can be applied to the North Sea can be applied to other non-oceanic coastlines. Thus there could be an export market for wave energy devices.

NATIONAL ENGINEERING LABORATORY WAVE POWER PROJECT

1 CONTEXT

The NEL Wave Power Project is one part of the UK effort to examine the feasibility of the extraction of power from sea waves. The programme which is being coordinated on a national basis by the Wave Energy Steering Committee (WESC) of the Department of Energy is at present concerned with the evaluation of the basic devices which are considered to offer the most promise. They are:

a Oscillating vane - Edinburgh University

b Floating pontoon - Wave Power Ltd

c Inverted can - National Engineering Laboratory

d Multi-level reservoir - Hydraulics Research Station

Types (a) and (b) may be categorised as mechanical devices, while types (c) and (d) can be reasonably described as hydraulic in nature.

2 THE INVERTED CAN

The wave power generator being developed at NEL is based on the inverted can principle. Incoming waves set up oscillations of the water column beneath the air trapped in the can. Energy can then be extracted either through an air turbine, water turbine, or a high pressure fluid power system, the choice being dependent on the purpose of the device.

For instance, simple inverted can navigation buoys, developed by Masuda of Japan, use a small air turbine-driven generator with storage batteries to provide sufficient electrical output for self-lighting. However, preliminary tests by NEL with the rudimentary shape (Fig. 1) rigidly held in a small wave tank have shown that it is capable of absorbing only about 30 per cent of the oncoming wave power. Theoretical studies indicated that this could be improved, and it has already been shown experimentally that quite elementary modifications to the design will increase the maximum efficiency to approximately 75 per cent.

3 NEL PROGRAMME

The objective of the NEL programme is to develop a practical system, involving a number of inverted can units stationed to absorb and generate power from waves along a wide front of the coastline. Precisely what will constitute a unit in terms of size and components will not be known until all the possible alternatives have been thoroughly examined. In very general terms the complete system will consist of:

a Primary conversion

The purpose of work on primary conversion is to transfer as much of the oncoming wave energy as possible into the oscillating water column. This will involve further development of the computer program, already partially complete, which gives numerical solutions of the hydraulic equations for any given geometry of inverted can. The application is at present limited to a rigidly fixed can, but must be extended to meet realistic full scale conditions, where it is necessary to consider dynamic response of the can to wave movement, within the constraints imposed by the mooring system.

These theoretical studies will be linked to experiments conducted in a simple wave tank, now under construction at NEL. The geometry of models tested will be specified by the computer analysis, and performance compared with that predicted. The models will first be held fixed, and then as the analysis develops, will be held in a complex linkage allowing simulation of movement, with mooring restraints, of the unit in a real seaway.

The ultimate objective of primary conversion studies is to develop a realistic shape which will operate at high efficiencies over a large frequency bandwidth.

b Rectification

If power is to be transmitted via a turbine, the input must be rectified, since the rotor inertia would be too great to permit rapid reversals of rotational direction. The main rectifying problem foreseen is the development of large reliable low-pressure non-return valves.

c Intensification

The primary conversion produces low pressure high volume energy, which can be handled directly only by large air or water turbines. A study must therefore be made as to whether the added complexity of intensifying the output to high pressure low volume energy can be justified by the overall saving in size which could thereby be achieved.

d Generation

This heading includes engineering design of the turbines or high pressure fluid power system, in consultation with designers of the driven electrical generating plant.

e Transmission and control

The problem of integrating the varying power output from a number of units strung along the front of oncoming waves with the customer source of electrical power demand is common to all wave power projects, and NEL will be advised in this aspect by a specialist group set up by the Wave Energy Steering Committee.

f Naval architecture

The units must ride the sea in such a manner as to allow efficient operation over a wide range of conditions, and must survive storms, subsequently recovering automatically to continue generation. Studies under this heading include general ocean engineering, particularly anchoring and mooring of structures.

All the above activities are strongly interdependent, and will therefore be pursued concurrently, with a developing concept of the entire system - seawaves to electricity consumer. There is particular NEL expertise in the following relevant areas.

(i) Wave power studies to date

(ii) Design of air and water turbines

(iii) General fluid mechanics

(iv) Fluid power systems

(v) Structural analysis and materials

(vi) Anchoring and mooring

Where expertise is not available within the Laboratory external consultants will be used - eg for naval architecture, electrical engineering. Wave loading of structures, anchoring, mooring, energy transmission and environmental studies are areas of common concern to all wave power teams. Any such work within a generic field will be seen within the requirements of the Wave Power Project on a national basis.

R A NIXON
Energy Division
5 March 1976

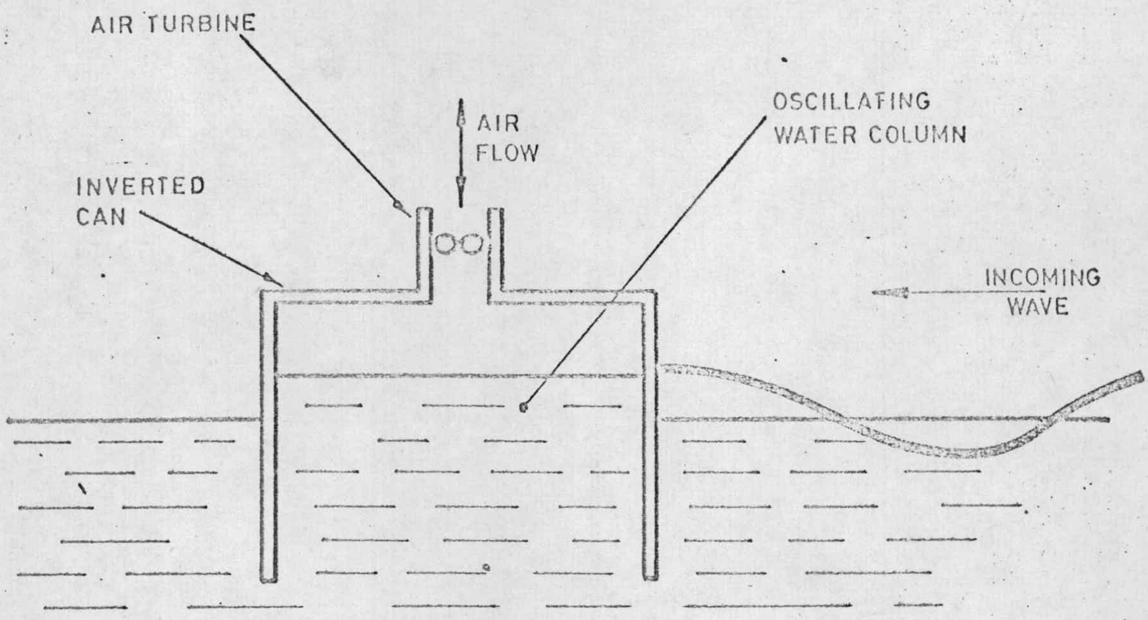


FIG 1 SIMPLE FORM OF INVERTED CAN

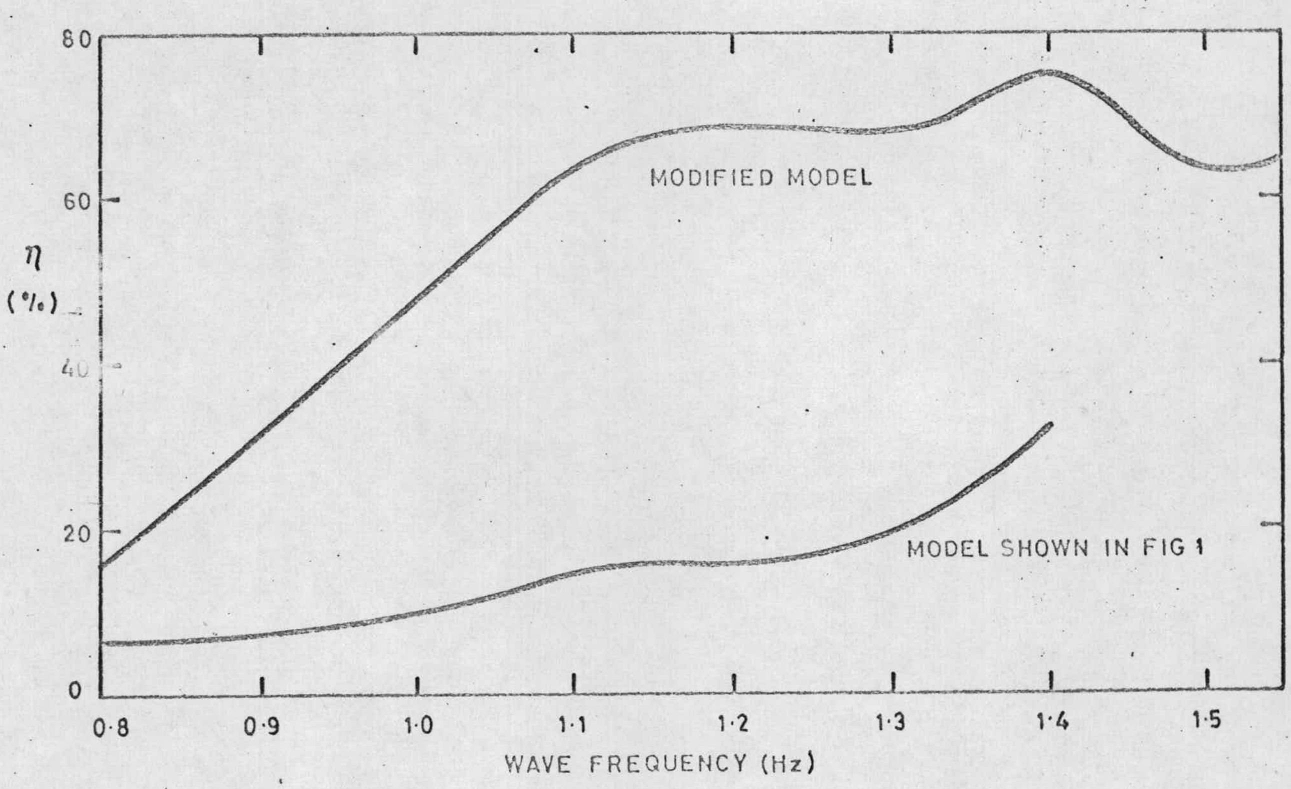


FIG 2 POWER ABSORPTION EFFICIENCY FOR SIMPLE AND MODIFIED FORMS OF INVERTED CAN

WAVES AT OCEAN WEATHER SHIP STATION *INDIA*

(59°N., 19°W.)

By L. DRAPER, M.Sc., A.Inst.P.,* and EILEEN M. SQUIRE*

Originally Published for Written Discussion

Summary

Two thousand four hundred wave records taken by Ocean Weather Ships in the North Atlantic have been analysed. Although taken over about thirteen years, the measurements should be representative of an average year. The results are presented in ways which, it is hoped, are of use to Naval Architects and Engineers. Wave height information is given in the form of percentage exceedance; this makes it possible to determine the percentage of time in which, for example, the significant wave height exceeded any specific height. Four such graphs are given, one for each season of the year. Wave period is given, for each season, as percentage occurrence of zero-crossing period. The percentage occurrence is given of the spectral-width parameter, for the whole year. Significant wave height is related to zero-crossing period in a scatter diagram, which illustrates the relative occurrence of the various conditions, and of the steepness of the waves. One such diagram is given, covering the whole year.

Waves have been recorded by Ocean Weather Ship *Weather Explorer* and then by her replacement, *Weather Reporter*, on stations A, I, J, and K in the North Atlantic since 1952. The instrument used is the Shipborne Wave Recorder.[1] The ship is on station for about two thirds of the year and her time is fairly evenly distributed over the four stations. The National Institute of Oceanography now has an adequate number of records from every month in the year at station *India* to allow an analysis to be made. In all, 2,400 records have been used; for each month they were selected at random from the ones which were available. The records were taken at 3-hourly intervals and almost all were of 12 minutes' duration, the exceptions being that in the month of March a few records of a slightly smaller duration were used to bring the total up to 200 for the month; the parameters measured from these were treated appropriately to make them comparable with the other results. The records which have been analysed were taken when the speed of the vessel was two knots or less, with the exception of a few which were taken when the ship's speed was up to 2·5 knots, because at higher speeds the apparent wave period is noticeably distorted. The method of analysis which has been used is that described by Tucker.[2] This gives for each record:—

(*a*) H_1 = The sum of the distances of the highest crest and the lowest trough from the mean water level;

(*b*) T_z = The mean zero-crossing period;

(*c*) T_c = The mean crest period.

From these measured parameters the following parameters have been calculated, after allowing for instrumental response:—

(*d*) H_s = The significant wave height (mean height of the highest one-third of the waves): this is derived from H_1 by using the relationship $H_1 = f \cdot H_s$, where f is a factor related to the number of zero-crossings in the record.[3] The numerical value of f for a record containing 100 waves is 1·60 and for 50 waves f = 1·49. These values of f are theoretical ones for a narrow-band spectrum[4] and have been shown to be substantially correct for typical wide-band spectra of sea waves.[3]

(*e*) $H_{max\,(3\ hours)}$ = The most probable height of the highest wave which occurred in the recording interval.[5] The designation "recording interval" is the name given to the interval which elapses between the starts of successive records.

(*f*) ϵ = The spectral width parameter [2] which is calculated from T_z and T_c: $\epsilon^2 = 1 - (T_c/T_z)^2$.

The results of these measurements and calculations are expressed graphically in relation to the seasons:—

Winter—January to March.
Spring—April to June.
Summer—July to September.
Autumn—October to December.

Because of the uneven distribution of the records throughout the individual months it was found convenient to take a "month" to start on the 23rd of the preceding calendar month, e.g. winter is based on records from December 23rd to March 22nd. This does not affect any conclusions drawn from the analysis.

Discussion of Results

From Fig. 1 it is easy to determine the proportion of time in which H_s or $H_{max\,(3\ hours)}$ exceeded any given height. For example, in the winter, the significant wave height exceeded 15 ft. for 41 per cent of the time. Wave heights and zero-crossing periods are substantially higher in the winter months than in any other season. The seasonal variation in the spectral width parameter is fairly small; the mean is slightly lower in the spring and summer months than during autumn and winter. The scatter diagram of Fig. 4 relates the significant wave height to zero-crossing period. The numbers of occurrences are expressed in parts per thousand. For example, the most common wave condition was that with a significant height of about 7 ft. and with a zero-crossing period of about 9 sec. The pressure units are necessarily situated at about 7 ft. below mean water level; because of the rapid attenuation of the shorter waves with depth, the instrument does not record waves which have a period of less than about 5 sec.; this is the cause of cut-off below that period. Higher waves are almost all associated with longer periods, but longer periods can also occur with lower wave heights, as when swell arrives from a distant storm. It will be

* National Institute of Oceanography.

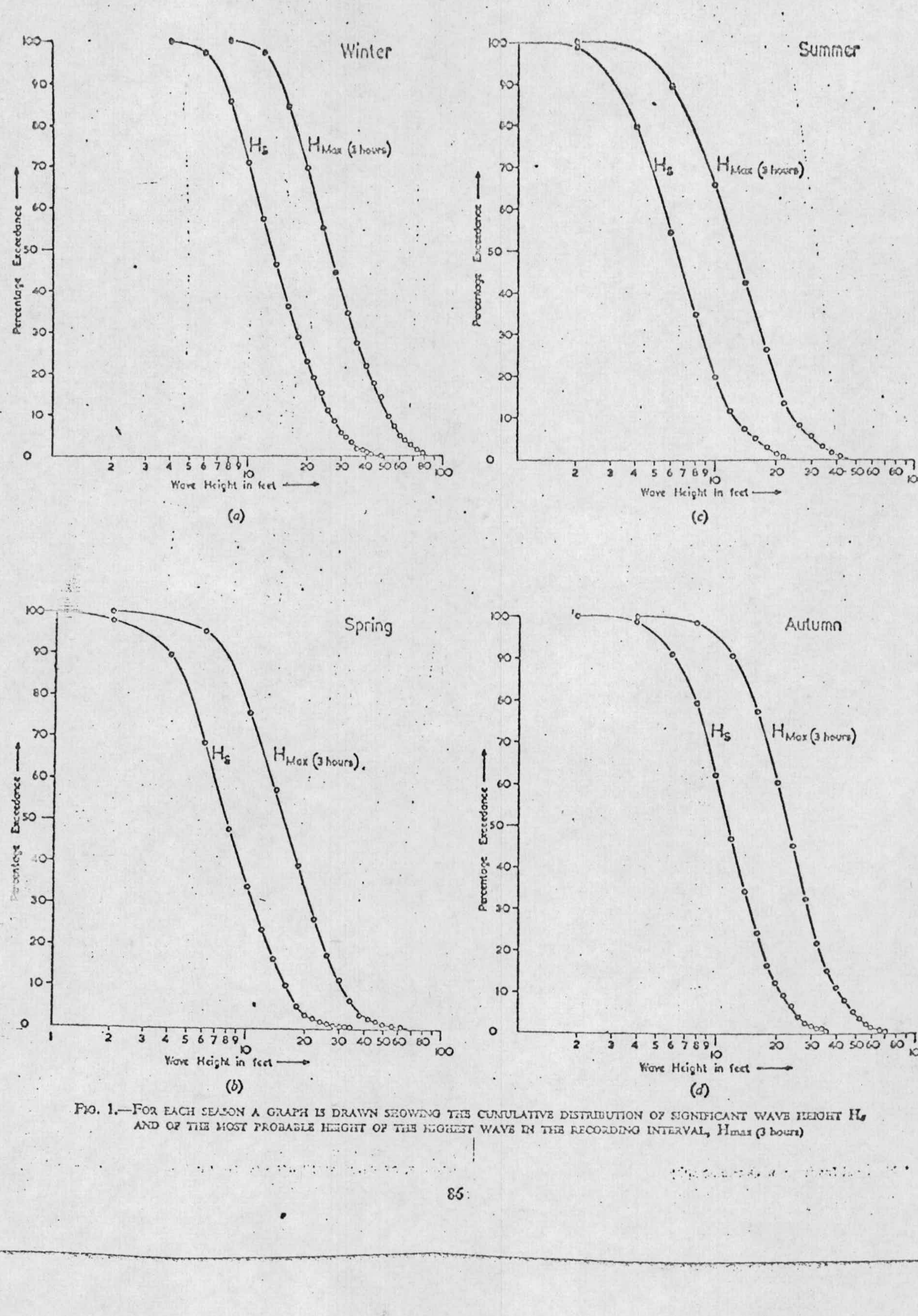


FIG. 1.—For each season a graph is drawn showing the cumulative distribution of significant wave height H_s and of the most probable height of the highest wave in the recording interval, H_{max} (3 hours)

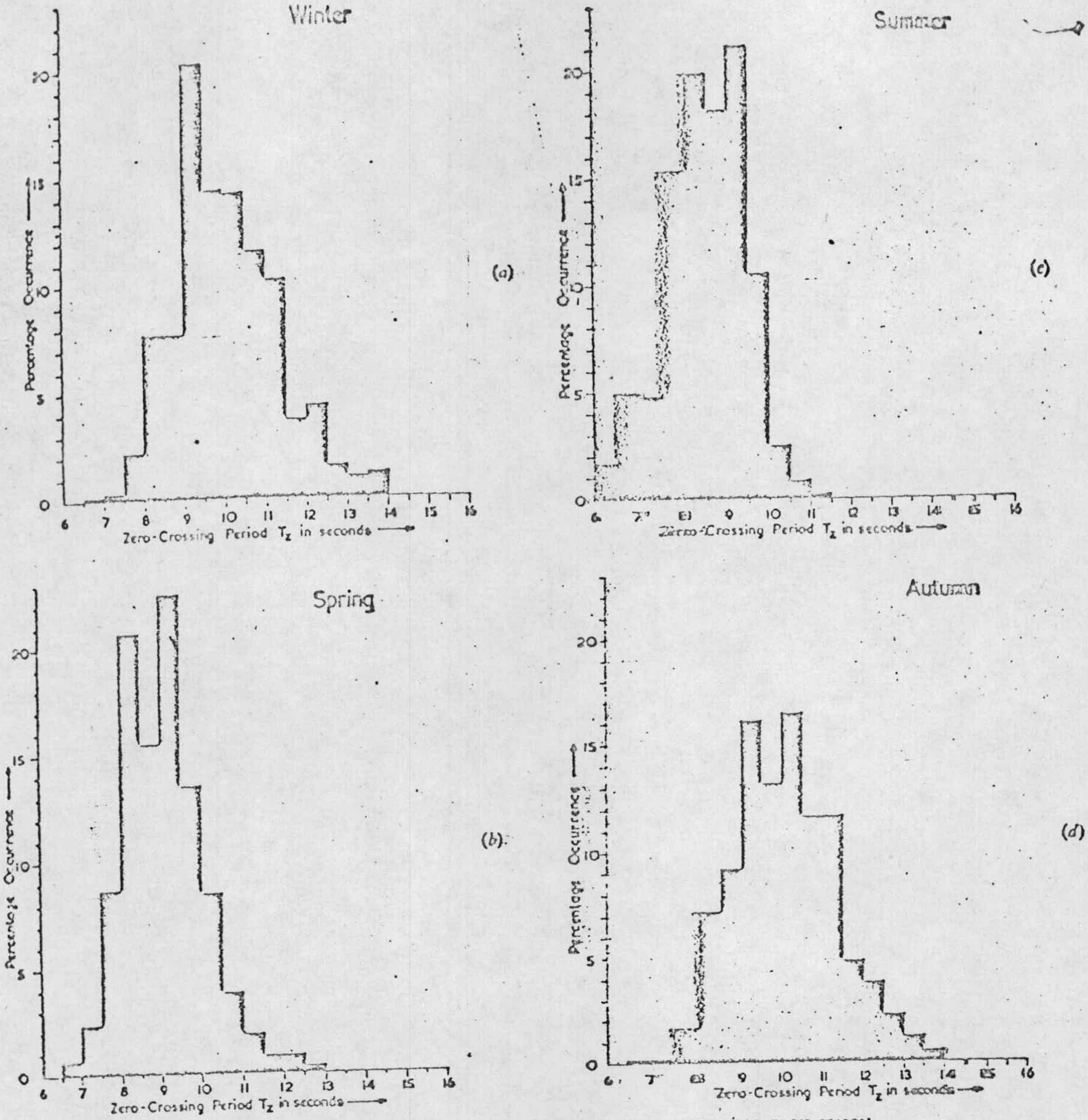


FIG. 2.—THE DISTRIBUTION OF ZERO-CROSSING PERIODS IS GIVEN FOR EACH SEASON

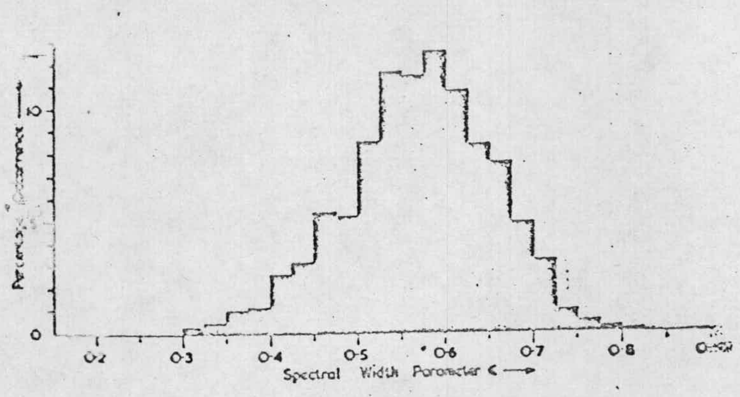


FIG. 3.—THE DISTRIBUTION OF THE SPECTRAL WIDTH PARAMETER IS GIVEN FOR THE WHOLE YEAR

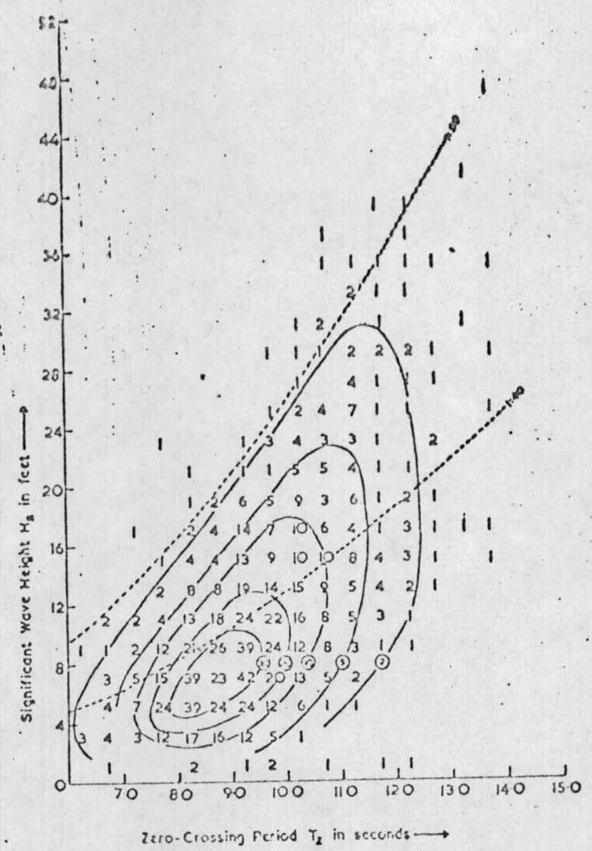


FIG. 4.—THIS IS A SCATTER DIAGRAM RELATING SIGNIFICANT WAVE HEIGHT TO ZERO-CROSSING PERIOD FOR THE WHOLE YEAR

seen that, in Fig. 4, the sums of figures in the columns will give a histogram of the distribution of period for the whole year; similarly the sums of figures in the rows will give a histogram of the distribution of significant wave height for the whole year.

A parameter which is sometimes of interest is the wave steepness, defined as the ratio of wave height/wave length. It should be noted that the steepness of a wave is not the same as the maximum slope of the water surface during the passage of a wave. Lines of constant significant-height-steepness of 1/20 and 1/40 are drawn on Fig. 4 (in this case steepness relates to significant wave height/wave length calculated from the zero-crossing period). A fairly well-defined limit of significant-height-steepness is observed at approximately 1/18 (0·056). There is a theoretical limit for a progressive wave of 1/7 (0·14); the steepest record actually observed in this series, using H_1 as the wave height, had a steepness of 1/8·35 (0·115) [defined as maximum H_1 observed (not significant height)/wavelength calculated from the zero-crossing period]. This occurred with a wave height of 35 ft. and of $T_z = 7{\cdot}65$ sec. Because the records were taken at random from a series covering about ten years, it is reasonable to assume that these are representative of a typical year.

The highest wave recorded by these vessels was one of 67 ft. crest to trough on September 12, 1961, at station *Juliett*. It seems possible that the highest wave which was experienced by *Weather Reporter* during that storm was about 80 ft. high.[6]

An analysis of wave conditions at O.W.S. station *Juliett*, based on 1,440 records, has recently been published.[7] As may be expected, the two stations show the same trends. The data in the present paper, being based larger on a number of records, shows less scatter than in the previous analysis. This enables, for instance, the information on Fig. 4 to be given in much more detail.

Wave collection by the National Institute of Oceanography is gradually building up a picture of wave conditions in sea areas around the British Isles. In addition to the paper mentioned above concerning waves at Ocean Weather Ship Station *Juliett*, conditions in the Irish Sea,[8] in the North Sea,[9] and in the Western Approaches[10] have already been described. Studies of wave conditions in the North Atlantic, based on Ocean Weather Ship visual observations, have been made by Walden[11] and Bunting[12] (unpublished manuscript).

The wave measurements taken by the Weather Ships, and also by several Trinity House Light Vessels, have been used by Professor J. Darbyshire in the development of his wave forecasting technique. The method has also been expressed graphically and was published[13] in 1963.

Wave Spectra

Details of North Atlantic wave spectra have been published in various journals. No information is included in this paper, but titles of a selection of publications are given in the References (14–20).

Acknowledgments

The authors wish to express their appreciation to the Meteorological Office for allowing their vessels to be used and to the Meteorologists and Electronic and Mechanical Engineers on the Weather Ships, and especially to Mr. R. H. Brass, for the care

they have exercised in taking the records and in ensuring the smooth running of the equipment. Without their continuing interest this information could not have been obtained.

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Three papers by MOSKOWITZ, L., PIERSON, W. J., and MEHR, E., with the title "Wave Spectra estimated from Wave Records obtained by O.W.S. *Weather Explorer* and O.W.S. *Weather Reporter*."

(18) Part I. New York College of Engineering, Research Division, Department of Meteorology and Oceanography, Technical Report, 1962.

(19) Part II. New York University Department of Meteorology and Oceanography, Geophysical Sciences Laboratory Report No. 63–5, 1963.

(20) Part III. As in No. 19 above, but this is Report No. 65–4 1965.

WRITTEN DISCUSSION

Commander, C. E. N. Frankcom: Visual wave observations in the oceans have been made voluntarily by the officers of merchant ships in some form or other since 1855. Since 1938 such observations have recorded direction, height and period of the waves. By this means many thousands of observations have been collected—but although wave direction is easy to estimate, there are obvious difficulties in estimating the height and period of individual waves aboard a moving ship. As ships become larger and their speed greater, these difficulties increase.

Aboard a relatively small ship, such as a weather ship or a trawler, such observations are much easier, particularly in the case of a weather ship which spends so much of her time stopped. Aboard a weather ship the observers height of eye is only 12 ft! Comparisons of the visual observations aboard the weather ships with those made in the merchant ships show that the merchant ship data are self-consistent but in general report a smaller frequency of high waves than the weather ships do.[21]

The existence of a wave recorder aboard *Weather Reporter* provides, for the first time, regular instrumental wave observations from a vessel permanently working in the North Atlantic and thus gives a ready reference for exact comparison between the visual observations in the weather ships and also in the merchant ships. This should facilitate statistical studies arising from the large number of merchant ship observations available in all oceans; obviously every merchant ship cannot be fitted with a wave recorder!

It is presumed that the maximum recorded height of 67 ft. during this twelve year period in the North Atlantic (and an estimated maximum of 80 ft.) does not mean that waves in excess of this figure cannot be experienced there or (say) in the Southern Ocean. It would be interesting to know if any greater wave height has been recorded by any other wave recorder in mid ocean.

From the mariner's viewpoint, it seems that the significant feature in this paper is the height/steepness ratio shown in Fig. 4. Presumably the steepest waves are sea waves.

Reference

(21) HOGBEN, N.: "Sea State Studies at the Ship Hydrodynamics Laboratory, Feltham," *Marine Observer*, p. 130, 1963.

Professor W. J. Pierson, Jr.: These valuable data are unique in the length of historical record obtained and the presentation by Mr. Draper and Miss Squire provides valuable statistics for the ocean area near O.W.S. station *India*. There are many useful facts to be obtained from analyses such as they have given.

We have had the privilege through the courtesy of Dr. Deacon and Mr. Draper of using the wave records obtained by the Tucker Wave recorder at stations A, I, J, and K in connection with the development of wave forecasting methods. Refs. (18), (19), and (20) provide a fairly large number of spectra estimated from these data that may be of value to naval architects.

In our analysis, after estimating the spectra, each frequency band was multiplied by the calibration factor provided by N.I.O.

(Ref. 22, for example), the total variance of the spectrum was found, and the significant height was computed from this total variance. In this work by Mr. Draper and Miss Squire, the significant height and average period were obtained as described, and then the height was corrected by means of the same calibration factor using the average period. Those whose application of these wave records is concerned with spectra would perhaps do well to go directly to the spectra tabulated in our reports as different spectra are affected differently when corrected over the full frequency range.

The processing of such a large set of observations rather necessitates the use of the more rapid procedures of the paper under discussion and for the purpose at hand the procedures are adequate. Mr. Draper has provided me with a set of 90 analyses that directly compare the significant height computed by us with the height obtained by their procedure. Our heights are, in general, a few feet higher, which may in part be explained by the fact that we amplify the high frequencies much more, proportionately, and by the fact that a small contribution at low frequencies, probably connected with noise and digitization error was not removed by us in the computation of the significant height.

For high waves, the two methods are in quite good agreement as the tabulation of the four highest significant heights in the sample of 90 shows. This suggests that the high wave tail of the distributions in the paper under discussion (Fig. 1) is likely to be quite accurate.

TABLE I

COMPARISON OF THE FOUR HIGHEST WAVES

Date	Time	NYU-H_s	NIO-H_s	Difference
23/12/59	0300	39·7	38·7	+1
10/12/58	1500	38·5	35·8	+2·7
10/12/58	1800	37·0	39·9	−2·9
8/11/59	0600	42·5	37·6	+3·9

For lower waves, 10 to 25 ft. high, the scatter in the comparison between the two methods is greater.

TABLE II

EXTREME DISCREPANCIES

Date	Time	NYU-H_s	NIO-H_s	Difference
19/ 4/58	0900	19·2	13·9	+5·3
24/ 5/58	1500	24·6	18·7	+5·9
8/11/59	1500	22·4	29·1	−6·7
10/11/59	0000	18·1	24·4	−6·3

This can be explained as at least in part due to the wide variety of spectral shapes that are found for the lower waves. A single period does not characterize the record too well under these circumstances. With reference to Fig. 1, these discrepancies probably cancel to a large extent with perhaps a slight, two feet or so, shift toward higher waves.

It is a pleasure to report that wave statistics are in general coming into better agreement between the different groups active in this area. Not too many years ago, the results of Professor Darbyshire seemed to indicate much lower waves for fully developed wind seas than we seemed to find in the United States. The explanation [see Ref. (22)] lies in the improved calibration of the Tucker wave recorder (as used in the paper under discussion) which has caused Professor Darbyshire to increase his original estimates of wave height and bring the various formulae relating wave height to wind speed into much closer agreement. It should be pointed out, however, that earlier work at N.I.O. did not use this improved calibration and that some of the tabulated height data may be too low.

For Professor E. V. Lewis of Webb Institute of Naval Architecture, we have spectrally analysed a number of extreme wave conditions as recorded by the Tucker recorder. Information on these extremes where H_s exceeded 40 ft. may be of value in connection with this paper and so the results are briefly given in Table III.

TABLE III

Date	Hour	H_s	90% Confidence interval	T
10/ 2/62 I	1800	54·7	67·4–44·5	9·1
12/ 2/62 I	1200	48·2	59·8–38·9	9·6
10/ 2/62 I	0900	42·6	51·9–25·0	8·2
26/ 1/61 I	1800	50·7	62·0–41·4	10·4
10/ 2/62 I	2100	50·4	62·1–40·8	9·9
16/ 2/62 I	0000	50·4	62·3–40·8	8·8
1/ 2/62 I	0000	44·6	56·0–35·5	9·7
15/ 3/64 J	0000	46·8	59·7–36·7	10·7
23/12/59 J	0300	41·5	52·1–33·1	10·9
17/12/59 J	1800	42·2	53·9–33·0	10·6
29/10/61 –	1800	42·0	51·0–34·0	10·3
3/ 1/60 –	1500	42·9	53·0–34·7	10·3
10/12/58 J	1800	49·2	61·9–39·1	9·9
4/11/62 J	1800	43·9	57·4–33·6	12·1
4/11/62 J	2100	50·1	64·4–38·9	12·1
2/ 3/63 J	0000	46·8	57·6–38·0	11·0

I have some reservations concerning the utility of the spectral width parameter in naval architecture. There is considerable evidence that the gravity wave spectrum behaves like $\alpha g^2/\omega^5$ at high frequencies. If it does, then one of the moments defining this parameter either does not exist or is completely controlled by the very high frequencies in the wave record. It is then highly dependent on total instrument response and should not be too useful in the frequency range of interest in naval architecture.

References

(22) DARBYSHIRE, J.: The high waves of September 1961. *In Studies on Oceanography* (Tokyo), 1964: pp. 329–33.

Mr. J. R. Scott, B.Sc.: The North Atlantic wave statistics presented in this paper will undoubtedly be of great interest to all concerned with the effect of sea upon ships. I find Fig. 4 of special interest because it permits comparison between zero-crossing periods assessed directly from wave records and some computed from spectra derived from such records.

The regression of T_z on H_s from the data of Fig. 4 for H_s greater than 10 ft. turns out to be

$$T_z = 0{\cdot}10\,H_s + 8{\cdot}5 \quad . \; . \; . \; . \; . \; . \quad (1)$$

That from the data of Refs. (18) and (19) turns out to be

$$T_z = 0{\cdot}084\,H_s + 6{\cdot}6 \quad . \; . \; . \; . \; . \; . \quad (2)$$

This is equation (6) in Scott,[23] where it was derived directly from the Moskowitz data in which the individual T_z were derived from spectra, not directly from wave records. The second equation predicts an average T_z shorter than that predicted by the first, by 2·1 sec. at H_s = 10ft. and by 2·5 sec. at H_s = 40 ft. This is an unexpectedly large bias, which cannot be attributed to differences between the two (large) samples concerned because both were drawn from the same population. Moskowitz *et al.* analysed their spectra over the period range 3 sec. to ∞, while the authors state that the wave recorder used does not record waves which have a period less than about 5 sec. (but see the Morecambe Bay data in M. Darbyshire's Fig. 9.[24]) It seems that the inclusion of the range of 3 to 5 sec. might have put a spurious high frequency tail on to the spectra presented by Moskowitz.

Because the wave recorder does not record waves of short period, the periods given in Fig. 4 are themselves overestimates of the T_z which occur on the sea surface, and it is of interest to estimate this bias. This was done by using a figure similar to Fig. 4 based on about 67,000 visual wave height (H) and period (T) observations made in the North Atlantic and summarized by Gerritsma[25] and Roll.[26] Regression of T on H using H greater than 10 ft. yielded

$$T = 0{\cdot}13\,H + 7{\cdot}0 \quad . \quad . \quad . \quad . \quad . \quad (3)$$

which estimates the bias as about +1·2 sec. for a 10 ft. wave and +0·3 sec. for a 40 ft. one; visual wave height is here identified with H_s. A similar comparison with equation (2) shows that the latter underestimates by 0·9 sec. for a 10 ft. wave and 2·2 sec. for a 40 ft. one, i.e.

$$\Delta T = 0{\cdot}046\,H + 0{\cdot}4 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

should be subtracted from a visual wave period observation as a preliminary to estimating the associated sea spectrum as described in reference.[23] This is the important part of the period bias mentioned in the conclusion of that paper.

I would like to conclude in lighter vein by asking the authors why the seasons at Station *India* are different from those at Land's End [Ref. (10)].

References

(23) Scott, J. R.: "A Sea Spectrum for Model Tests and Long-term Ship Prediction," *J. of Ship Research*, 1965.

(24) Darbyshire, M.: "Sea Waves in Coastal Waters of the British Isles," *Deut. Hydro. Zeit.*, 1962.

(25) Gerritsma, J.: "Dimensions of Sea Waves on the North Atlantic," *Int. Shipbuilding Progress*, 1954.

(26) Roll, H. U.: "Height, Length and Steepness of Sea Waves in the North Atlantic," *Tech. & Res. Bulletin, Nos.* 1–19, S.N.A.M.E.

Mr. E. C. B. Lee (*Member*): One application of the data in this excellent paper concerns the design of liferaft lights which will be visible to an observer on a ship when the raft is within a vertical distance of 4 ft. 6 in. of the wave crest. The naval architect has the choice of a steady light, which will be visible when the raft is within the 4 ft. 6 in., or the much brighter flashing light whose period of flash is a small fraction of a second and which will only be seen when the flash occurs within this distance of the crest. The data indicates that the period between flashes should be much less than 6 sec. and I would be glad of the authors' advice on what the period should be. Their remarks as to whether this period would be applicable to other seas and oceans would also be appreciated.

Mr. N. Hogben, B.Sc., Ph.D. (*Associate-Member*): The authors have done an outstanding service to Naval Architects and others concerned with ocean waves by presenting this analysis of such a large sample of wave measurements. In recent years several rather extensive compilations of visual wave statistics have been prepared and it is of great importance to know how such observed data compare with corresponding measured results. In Fig. 5 (*see next page*) statistics based on voluntary ship observations taken from 2 independent compilations, Refs. (27) and (28) are shown in comparison with the data of the present paper plotted in the form of Fig. 1. The visual data refer in each case to much larger areas than the measured results. It is interesting to note however that in all cases the measured curves lie above the visual ones. This appears consistent with results reported in Ref. (29) showing that similar curves based on weather ship observations lay consistently above corresponding curves from voluntary ship observations.

Reference

(27) "Report of Environmental Conditions Committee of the International Ship Structures Congress," Delft, 1964.

(28) Hogben, N., and Lumb, F. E.: "Ocean Wave Statistics" HMSO publication in preparation, See *Marine Observer*, April 1965.

(29) Hogben, N: "Sea State Studies at the Ship Hydrodynamics Laboratory, Feltham," *Marine Observer, July* 1963.

Authors' Reply

To Cdr. C. E. N. Frankcom:—

It is extremely unlikely that from one vessel stationed in the North Atlantic we have recorded the highest wave possible in that ocean. The highest recorded wave height known to the authors (as distinct from visually estimated heights) is that taken from a stereophotograph of an Antarctic storm by a Russian research vessel, giving a crest-to-trough vertical separation of 24·9 metres, or 82 ft. This technique has the advantage that when looking at an area of confused sea the highest crest and lowest trough can be measured, whereas any single-point instrument in the same sea would be most unlikely to be traversed by the two extremes of the wave. The areas occupied by the extreme crest and extreme trough at the instant the photograph was taken were very small. The horizontal separation of crest and trough was about 190 metres.

The steepest waves are those under the influence of the generating winds.

To Professor W. J. Pierson:—

The agreement between methods is most encouraging and gives confidence in the use of the various techniques. For any individual record the values of H_s derived by our methods are subject to the same statistical scatter as the heights of the waves. However, when the analysis contains nearly 3,000 measurements such scatter is of no importance. For individual records the significant heights produced by Professor Pierson from the whole record are more reliable than those we obtained from the two extremes, although if desired we can reduce the scatter in our method by taking note of several other high crests and troughs. The first two N.I.O. papers presenting analyses of wave data Refs. (8) and (9) are the only ones using the earlier calibration factors, and the data were re-presented in Ref. (30) using the new factors.

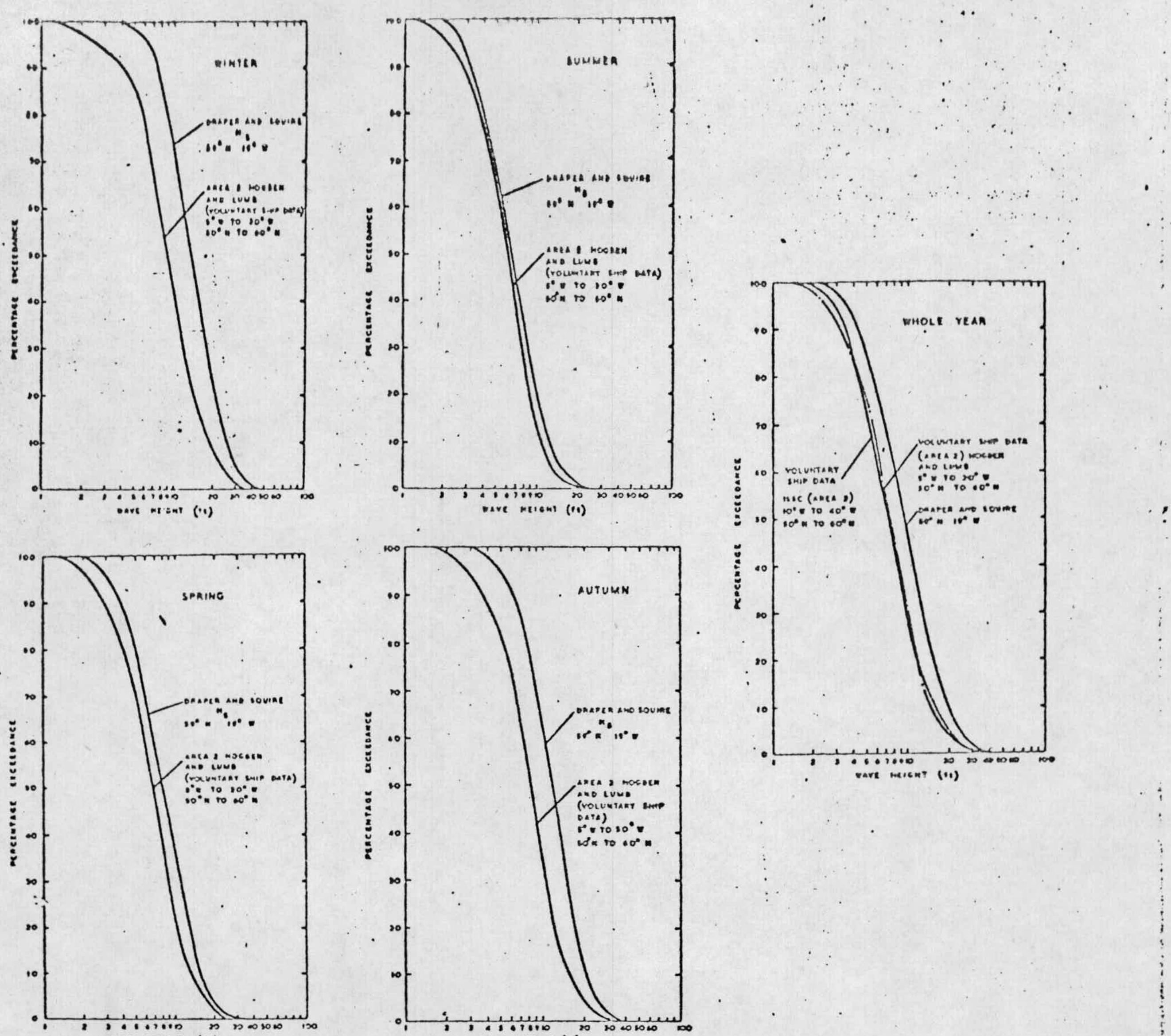

FIG. 5 (*see contribution by Dr. Hogben on previous page*)

To Mr. J. R. Scott:—

We find it surprising that Mr. Scott should take the trouble to prove mathematically that two obviously different samples from the same population have different characteristics. The data in our paper represent a complete year's wave conditions whereas Moskowitz, using our records from several Ocean Weather Ship stations, chose conditions where swell was unimportant so that he could derive a wind–wave relationship. Also, Mr. Scott arbitrarily omits waves with a significant height of less than 10 ft.; if he had removed all data where the steepness was less than some particular value he would have stood a much better chance of producing two similar equations, although we again fail to see what this would achieve. The visual observations of T, which can only loosely be defined, cannot be expected to agree exactly with measurements of T_z; neither can visual estimates of H be expected to compare strictly with H_s. (See Dr. Hogben's contribution to the Discussion.)

Both our analyses and Moskowitz's use the same response curves; the phrase "less than about 5 sec" was used because the response falls to half at a period just below 5 seconds, but it is known at all periods and Moskowitz chose to use it down to 3 seconds. The response factors at short periods depend on the depth of the unit below mean water level, so that in a Light Vessel such as that at Morecambe Bay, which is small in comparison to a Weather Ship, the units can be nearer the surface; this results in different responses in different sizes of ship, as observed in the publications by Mr. Scott. The errors introduced into T_z by the response curve will be fairly small, and it is debatable whether they are of importance to Naval Architects.

Concerning the seasons: The Weather Ship's tours of duty give irregularly-spaced sets of data, so the "months" were taken such that each month's duration contained an equal amount of data. For each station the seasons were defined so that in general the stormiest conditions were grouped into the winter and the quietest into the summer. The change-over from autumn to winter conditions probably occurs during December, and in one case it was more logical to include the December data in winter and in the other to exclude it.

To Mr. E. C. B. Lee:

The problem of frequency of occurrence of light-flashes from life-rafts must also involve such problems as battery life and size, as well as light intensity. From the wave point of view the interval ought to be fairly short, perhaps as low as 1 second, so that several flashes could occur whilst the craft sits near the top of each wave. However, as battery-power must be conserved, it is possible to estimate a maximum interval which will give above-crest-level flashes for most of the time. Considering the case when the significant height of a fully-developed sea in shallow-waters is 4 ft. the zero-crossing period will be between 5 and 6 seconds; (in oceanic waters the period will be slightly longer). In this condition the light at 4 ft. 6 in above the sea will be above the local crest levels for a large proportion of the time; for less severe conditions it will be above crest level virtually all the time. Obviously a 5-second-interval flash will be obscured relatively rarely in these conditions, even when the flash-interval and wave period synchronize. In worse weather the wave period will be longer so that there will be very few long sequences in which the light will flash only when the raft is near a trough. It therefore seems reasonable to suggest that flashes should be at intervals not longer than 5 seconds and preferably at about 4 seconds.

These calculations are for wind-generated waves and should apply to all sea areas.

Reference

(30) Darbyshire, Mollie: "Wave measurements made by the National Institute of Oceanography," *Marine Observer*, January 1962.